Volume 26 SEPTEMBER, 1956 Number 3

Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
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The American Association of Petroleum Geologists

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Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

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Among papers to appear in forthcoming issues of the *Journal* are the following:

Multivariate analysis of mineralogic, lithologic, and chemical composition of rock bodies. By W. C. Krumbein and John W. Tukey.

Sediment distribution in the southern oceans around Antarctica. By Jack L. Hough

Sedimentary structures in the Upper Carboniferous of north and central Derbyshire, England. By John Trevor Greensmith

Heavy-mineral suites in the unconsolidated Paleocene and younger sands, western Tennessee. By Reginald R. Blankenship.

Sandy zones in the Chattanooga of the Eastern Highland Rim, Tennessee. By Stuart W. Maher.

Examples of probable lithified beachrock. By William F. Tanner.

Thickness of strata. By Vincent C. Kelley.

Announcement of Meeting

GULF COAST ASSOCIATION OF GEOLOGICAL SOCIETIES

October 31–November 2, 1956. Gulf Coast Association of Geological Societies, 6th Annual Convention, Plaza Hotel, San Antonio, Texas

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 26, NO. 3, PP. 213–221
FIGS. 1–2, SEPTEMBER, 1956

THE MULTIPLE-CONE SAMPLE SPLITTER[1]

RICHARD C. KELLAGHER AND FRANCIS J. FLANAGAN
U. S. Geological Survey, Washington 25, D. C.

ABSTRACT

A multiple-cone sample splitter, consisting of a series of powder funnels and inverted brass cones mounted alternately in a vertical column over a tray containing small sector-shaped pans, shortens the time necessary to reduce samples to grain-counting size by about 75 percent.

A sample design has been set up by which three methods of sample splitting for grain counting—the microsplit, the cone splitter, and hand-quartering—may be compared. The methods of sample splitting are used for one classification in the design and the sample weights of 5, 10, and 20 grams of known grain composition for the other classification. Only one subset of data—that of the 5-gram sample split by the cone splitter—showed a value of χ^2 for precision that was equal to or less than that expected from chance alone. Similar calculations for estimates of accuracy show that the 5-gram sample by the cone splitter and the 10-gram sample by hand-quartering do not exceed the χ^2 values due to chance alone. If the subtotals of the 3×3 experimental design are used to calculate χ^2, it is seen that: (1) the splitting of the 5-gram sample by all methods is both more accurate and more precise than the splitting of the other two sample weights; and using the three weights for each method (2) the microsplit is the least accurate and the least precise of the three methods, (3) the hand-quartering is slightly more precise than the cone splitter, and (4) the cone splitter is slightly more accurate than hand quartering.

INTRODUCTION

In connection with studies of the monazite sands of the southeastern United States approximately 3000 samples were collected for grain-count analysis. These samples were received as panned concentrates ranging in weight from 10 to 400 grams and consisted of unsized mixtures of heavy minerals. Each sample was sieved into three size fractions, and a sample of approximately 300 to 500 grains was split from each of these for analysis.

With conventional methods of sampling (Otto, 1933; Taggart, 1947; Milner, 1940; Krumbein and Pettijohn, 1938) using the Jones splitter, the microsplit, and hand-quartering, in which the sample is split in half for each pass, approximately nine passes are required to reduce a 5-gram sample to counting size. This results in a disproportionate amount of time being spent in sampling the material.

In an attempt to shorten the sampling time a multiple-cone splitter was designed to obtain a representative fraction of 2.5 to 50 percent in one operation. The time required for the splitting operation is reduced by about 75 percent. Tests were then conducted to compare the accuracy and precision of the cone splitter with that of the microsplit and hand-quartering methods. The microsplit used in the test measures 1 inch square at the top and has 14 alternating chutes.

We wish to acknowledge our discussions of this problem with R. M. Garrels and G. J. Jansen of the U. S. Geological Survey and to thank W. J. Youden and W. H. Clatworthy of the National Bureau of Standards for their advice on the statistical solution of the problem. Jerome Stone of the Geological Survey assisted in checking the grain counts, and Camillo Massoni, also of the Geological Survey, built the cone splitter. This report concerns work conducted by the Geological Survey on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

[1] Publication authorized by the Director, U. S. Geological Survey.

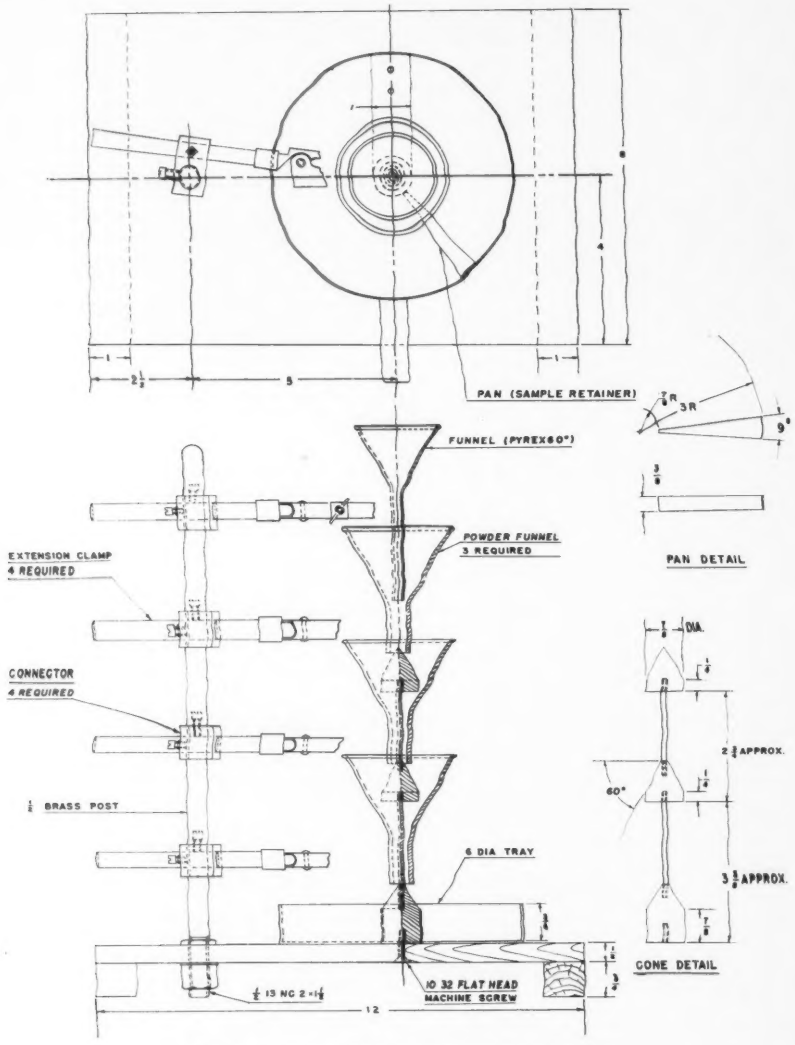

FIG. 1.—Details of the multiple-cone sample splitter.

DESCRIPTION AND OPERATION OF THE MULTIPLE-CONE SAMPLE SPLITTER

The multiple-cone sample splitter consists of three powder funnels and three brass cones mounted alternately in a vertical column with a cone at the base and a plain long-stem 60° funnel above the top powder funnel to direct the stream of grains onto the apex of the top cone. This assembly, mounted on a wooden base approximately 8 in. × 12 in., is shown in figures 1 and 2.

The three cones are stationary, spaced approximately 2 to 3 in. apart, and are supported by a steel rod bolted to the base in a vertical position. The powder funnels are held in adjustable clamps mounted on a brass post bolted to the base in a vertical position. When assembled, the funnel stems are centered over the cones by the adjustable clamps. Below the basal cone and surrounding it is a circular stainless-steel tray 6 in. in diameter with a wall height of $\frac{3}{4}$ in. The tray consists of a removable section and a section fixed to the wooden base with screws, limiting the tray to one position. The split tray permits rapid removal of the sample and facilitates cleaning.

Small sector-shaped pans are used as sample retainers. The pans have walls $\frac{3}{8}$ in. high and each pan includes an arc of 9° or approximately 2.5 percent of the area of the circular tray. One or more of these pans can be used depending on the amount of the initial sample and the amount of the sample needed for analysis. When a sample is to be split, the retainers are placed in the tray like spokes in a wheel.

The sample splitter should be in a level position with all funnels centered over their respective cones before a sample-splitting operation is begun. A trial run can be made to check the distribution of the sample in the tray, and if the distribution is uneven an adjustment of the funnels should be made. With care the sample splitter will remain in operating condition indefinitely.

The sample to be split is poured into the small funnel at the top of the column and flows to the apex of the first cone where it is thrown to the walls of the next funnel and then flows to the next cone. This is repeated at the next funnel and basal cone. The sample is distributed about the basal cone in the circular tray where the sector-shaped pans capture the desired portion. The total amount of sample retained can be varied by the addition or removal of sample pans. Adjustment of the gap between each funnel and cone can be made to accommodate different size fractions and to control the rate of flow of the sample through the splitter. The gap between the basal cone and funnel controls the spread of the sample in the tray.

The apparatus is easily cleaned by removing and emptying the tray and sample pans and sweeping the tray, funnels, and cones with a soft brush.

COMPARISON OF SAMPLE SPLITTING METHODS

Otto (1933), reporting test data obtained on three methods of sampling using eight ternary mixtures so selected that influencing factors could be studied nearly independently of each other, concluded that the microsplit was more accurate and more rapid than the improved Krumbein and the Pettijohn methods (Otto, 1933). Unfortunately, Otto does not give the known grain composition of his mixtures. Wentworth and others (1934) devised a rotary type of sample splitter and after testing concluded that their splitter is more accurate than the Jones splitter. They further conclude, after comparing their deviations and those of Otto, that all methods are approaching the theoretical values. They do not state, however, the nature of these theoretical values.

The time required for splitting a sample in half using a microsplit is estimated at half a minute. A 500-grain sample of −80+100 mesh quartz weighs about 5

FIG. 2.—The multiple-cone sample splitter.

mg. To reduce a 5-gram sample of this material to 500 grains would require about ten splits and consequently about five minutes. Hand-quartering requires a longer time to make ten splits. Little time is involved in splitting a small number of samples. For 100 samples, however, 2 days would be required for the splitting operation alone and more than two weeks for 1000 samples.

TABLE 1.—*Grain frequency composition of the test samples*

Mineral	Average wt/grain (grams)	Number grains/gram	Grams/5 grams of sample	Grain frequency (percent)
Quartz	8.46×10^{-6}	1.186×10^{5}	1	38.57
Ilmenite	17.36×10^{-6}	5.760×10^{4}	2	37.46
Monazite	27.13×10^{-6}	3.686×10^{4}	2	23.97

The cone splitter can reduce a 10-gram sample to about 500 grains by taking two consecutive 2.5 percent splits of the sample. These two operations of the cone splitter take about one minute and result in a saving of about 75 percent in sampling time.

PRECISION AND ACCURACY

The cone splitter has been shown to have an advantage in that the time required for its operation is much less than that required for the other methods. This comparison of the rapidity of operation is a straightforward procedure and estimates of the time necessary for splitting can be made by mathematical considerations; the accuracy and precision of the method are not so simple to estimate. Shape, size, density, and numbers of grains may affect the splitting operation as may also the sample weight and the number of passes required for the final split.

Although most investigators of splitting operations use the weight percent or the volume percent obtained by splitting samples of unknown composition and term their results accuracy instead of precision, it is axiomatic that to estimate the accuracy of the splitting operation one must know the composition of the original sample to be split. The best estimate of this composition is the actual grain frequency percent of the constituents of the sample used. To obtain this composition six samples of approximately 600 grains of each of the pure minerals were counted and weighed. From these data the average weight per grain, its reciprocal, the number of grains per gram, and the grain frequency composition were calculated (table 1).

A simple 3×3 two-way classification experimental design with triplicate replications was set up in which one classification was the methods used, that is, the microsplit, cone splitter, and hand-quartering, and the other classification was increasing weights of sample to be split. The three samples were artificial mixtures of quartz, monazite, and ilmenite, all −80+10 mesh in a weight ratio of 1:2:2, respectively, and weighed 5, 10, and 20 grams. Each sample was split to final or counting size (approximately 700 grains) by each method. All splitting operations were performed by one man. The final split was counted by operator A, checked for gross counting errors by operator B, and the split returned to the original sample before resampling. The grain counts of these final splits are shown in table 2. Only the grain counts by operator A have been used in the calculations below.

The observations made in this kind of test are total grain counts of each mineral constituent counted on a slide under a binocular microscope. As seen from table 2, the problem resolves itself into one of enumeration statistics, calculations for which are shown in any introductory statistics book, for example, Dixon and Massey (1951). The problem is further resolved into two distinct classifications: (1) the estimation of the precision of the splitting operation, and (2) the estimation of the accuracy.

Calculations in enumeration statistics may be carried out using the statistic χ^2 which is readily calculated by the formula

$$\chi^2=\sum_{i=1}^{k}\frac{(G_O-G_E)^2}{G_E}$$

where G_O is the observed grain counts of a mineral and G_E the expected counts. The expected counts are obtained from the experimental grain counts for precision and from the original sample composition for accuracy. For example, using the counting data of operator A for the 5-gram sample split by the cone splitter and inserting the marginal totals as shown in the following tabulation,

Sample	Quartz	Ilmenite	Monazite	Total
1	357	339	219	915
2	226	206	144	576
3	231	215	151	597
Total	814	760	514	2088

one obtains the expected number of quartz grains for sample 1 by multiplying the grain total of sample 1 by the ratio of the total quartz grains in the three samples, to the total number of grains. Numerically this would be

$$915 \times 814/2088 = 357.$$

This expected number of grains is used for estimates of precision. For the estimation of accuracy the ratio above is replaced by the proportion of the mineral in the original sample. The expected number of quartz grains then becomes

$$915 \times 0.3857 = 353.$$

TABLE 2.—*Grain counts of splits of three samples*

Method	Split	Operator	5 grams				10 grams				20 grams			
			Q[1]	I[2]	M[3]	Total	Q	I	M	Total	Q	I	M	Total
Microsplit	1	A	219	145	243	607	157	326	190	673	311	233	299	843
		B	223	144	243	610	174	328	190	692	310	232	292	834
	2	A	321	315	224	860	216	377	272	865	186	195	160	541
		B	340	330	230	900	198	374	268	840	180	209	149	538
	3	A	162	180	107	449	139	185	135	459	322	328	205	855
		B	166	183	108	457	133	185	132	450	310	328	209	847
Cone splitter	1	A	357	339	219	915	401	436	239	1076	249	217	138	604
		B	356	336	222	914	390	430	242	1062	240	216	135	591
	2	A	226	206	144	576	338	280	204	822	254	155	84	493
		B	219	208	141	568	324	269	210	803	243	158	83	484
	3	A	231	215	151	597	248	268	163	679	434	295	219	948
		B	236	214	151	601	242	247	169	658	420	288	227	935
Hand-quartering	1	A	201	217	178	596	238	240	150	628	219	257	149	625
		B	181	218	194	593	223	232	149	604	204	238	144	686
	2	A	418	308	248	974	237	250	169	656	270	180	121	571
		B	396	308	247	951	211	240	152	603	251	178	128	557
	3	A	262	248	187	697	233	197	110	540	347	189	132	668
		B	260	255	187	702	230	203	112	545	352	201	132	685

Average grain count = 695

[1] Q—Quartz.
[2] I—Ilmenite.
[3] M—Monazite.

A typical calculation of χ^2 for precision for the 5-gram sample split by the cone splitter (operator A) is shown in table 3.

χ^2 thus calculated can be used in either a qualitative or quantitative manner. In the qualitative sense we can use the calculated chi squares, especially where they exceed table values, to rank the variables, in this case by the method of splitting or the sample weights.

To draw quantitative conclusions from χ^2 values one must refer to a table of the χ^2 distribution to determine if the calculated values exceed the theoretical values. These tables have two variables, (1) the probability interval that the investigator chooses, in this case, 95 percent, and (2) the degrees of freedom (d.f.) which are dependent on the experimental design. In normal enumeration problems where an estimate of precision is the goal, the degrees of freedom may be calculated from the expression d.f. $=(n-1)\ (k-1)$ where the design has n rows and k columns of data.

Logically, the degrees of freedom may be developed as follows: referring to the foregoing tabulation, there is originally one degree of freedom for each mineral in each sample, or in this case a total of 9. If we total the minerals across the rows, we use up one degree of freedom for each total as, knowing the total, only two of the three minerals can be independent. For three row totals we lose three degrees of freedom. The grand total may be then determined from the row totals without loss of a degree of freedom. As we now know the grand total, one column total will be determined once we know the grand total and the other two column totals. From the original 9 degrees of freedom we must subtract 3 lost in calculating row totals and 2 lost for columns total, leaving 4 degrees of freedom available for estimate of precision.

For estimates of accuracy, we know the grain frequency proportions, which, for precision, are calculated from the grain column totals and the grand total. Hence, we do not lose the two degrees of freedom associated with the column totals and we have therefore six degrees of freedom available for estimates of accuracy. The calculated χ^2 values for precision for each of the subsets of data in table 2 are shown in table 4 and those for accuracy in table 5.

TABLE 3.—*Typical calculation of* χ^2

Sample No.	Mineral	Grains observed G_O	Grains expected G_E	$\frac{(G_O-G_E)^2}{G_E}$
1	Quartz	357	357	0
	Ilmenite	339	333	0.108
	Monazite	219	225	0.160
2	Quartz	226	224	0.018
	Ilmenite	206	210	0.076
	Monazite	144	142	0.028
3	Quartz	231	233	0.017
	Ilmenite	215	217	0.018
	Monazite	151	147	0.109
				$\chi^2 = \sum = 0.534$

TABLE 4.—χ^2 *for precision using subsets of counting data*

Weight (grams)	Micro-split	Cone splitter	Hand-quartering
5	114.60	0.67	34.90
10	19.32	19.17	15.68
20	88.18	31.55	77.17

TABLE 5.—χ^2 *for accuracy using subsets of counting data*

Weight (grams)	Micro-split	Cone splitter	Hand-quartering
5	100.47	2.13	30.17
10	93.53	22.87	8.09
20	79.15	46.04	73.39

If one compares the calculated χ^2 values for precision in table 4 with the theoretical values of 0.484 and 11.14 for the 95 percent confidence interval for 4 d.f., it is seen that the calculated value for only one of the subsets lies within the theoretical limits. It may be concluded then that the observed grain counts for this subset of data do not differ from those expected from chance alone.

TABLE 6.—*Subtotals of data in table 2 tabulated by method and by sample weight*

Method	Microsplit				Cone splitter				Hand-quartering			
	Q[1]	I[2]	M[3]	Total	Q	I	M	Total	Q	I	M	Total
5 grams	702	640	574	1916	814	760	514	2088	881	773	613	2267
10 grams	512	888	597	1997	987	984	606	2577	708	687	429	1824
20 grams	819	756	664	2239	937	667	441	2045	376	626	402	1864
Total	2033	2284	1835	6152	2738	2411	1561	6710	2525	2086	1444	5955
Weight	5 grams				10 grams				20 grams			
Microsplit	702	640	574	1916	512	888	597	1997	819	756	664	2239
Cone splitter	814	760	514	2088	987	984	606	2577	937	667	441	2045
Hand-quartering	881	773	613	2267	708	687	429	1824	836	626	402	1864
Total	2397	2173	1701	6271	2207	2559	1632	6398	2592	2049	1507	6148

[1] Quartz.
[2] Ilmenite.
[3] Monazite.

Comparison of the values for accuracy, for which the limits for the 95 percent confidence interval for 6 d.f. are 1.24 and 14.45, shows that only two subsets of data show grain counts which do not differ from those expected from chance alone.

Qualitative conclusions can be made concerning the methods and the weights. The subtotals of each of the nine subsets of the data, the values for which are shown in table 6 may also be used to calculate χ^2 in the same manner as shown previously. As the data presented in this table represent all the data in the experiment we shall classify our calculations according to (1) methods of splitting and (2) sample weights, and each of these classifications may be treated with respect to (a) precision and (b) accuracy. The results of these two types of calculations for the nine subtotals are shown in table 7.

These numerical results can be used for the purpose of ranking. This is done by calling best that method (or sample weight) with the lowest value of χ^2 and, conversely, the method with the highest value would be the worst. The ranks thus obtained from the data in table 7 are obvious.

Although we have used only the grain counts for operator A for our calculations, the data in table 2 are of further interest in that we can determine whether or not the grain counts of the operators differ. As pointed out by Youden (1951, p. 28), if we pair the individual mineral counts and take the differences between n pairs of counts we can then calculate the average difference, $\bar{d}$, (which is equal to the difference between the average count of the operators) and its standard deviation, s_d. By appropriate substitution in the equation $t=\bar{d}\sqrt{n}/s_d$ we obtain a numerical value for t of 2.48 which is

TABLE 7.—χ^2 *for precision and for accuracy, calculated by methods and by sample weights*

	Methods			Weights		
	Micro-split	Cone splitter	Hand-quartering	5 grams	10 grams	20 grams
Precision	183.30	57.88	55.05	27.06	195.94	177.44
Accuracy	435.72	82.78	90.33	110.79	287.99	210.06

significant at the 95 percent but not at the 99 percent level. We can then conclude, with 1 chance in 100 of being wrong, that there is not a significant difference between the grain counts of the two operators. For this discussion, however, the question of a significant difference between the grain counts of the operators is academic as the counts of operator B were made merely to check those of A for gross errors.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 26, NO. 3, PP. 222–227
FIGS. 1–4, SEPTEMBER, 1956

A COMPARISON OF TWO METHODS FOR CONVERTING GRAIN COUNTS TO WEIGHT PERCENT COMPOSITION[1]

R. C. KELLAGHER AND FRANCIS J. FLANAGAN
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ABSTRACT

Differences in experimental weight percent composition obtained in a recent study of sampling methods, when compared to the known composition of the original sample, have led to the reassessment of the method of computing weight percent composition from grain counts. The concept of average weight per grain of each mineral was used in place of the frequently used specific gravity factor method. The differences in the results calculated by specific gravity factors and by average weights per grain can be seen to be significant by inspection. Comparison of the mean percentages of the minerals shows that the results obtained using the concept of average weight per grain are the best estimates of the known weight percent composition.

INTRODUCTION

In connection with recent studies of monazite sands of the southeastern United States by the U. S. Geological Survey on behalf of the U. S. Atomic Energy Commission, a large number of samples was collected for grain count analysis. An investigation of sample-splitting methods (Kellagher and Flanagan, preceding paper) used in this monazite program provided grain counts of prepared test samples. Comparison of the weight percent composition of these test samples, as calculated from the grain counts, with the actual sample compositions showed serious discrepancies and indicated that substantial errors might be caused by the grain density factor in the method of calculating weight percent composition from grain counts.

In most geologic investigations the weight percent composition of sized and mixed mineral aggregates is obtained conveniently from a grain count of small portions of the sample. This grain count is used as a measure of the volumes of the minerals contained in the sample and is converted to weight by multiplying by the respective mineral densities according to the relation, weight = volume × density.

It is apparent that the accuracy of these weight determinations depends upon the assumption that all of the mineral grains are of equal volume. However, differences in volume due to shape, degree of roundness, and relative size among minerals cannot be ignored, and attempts have been made to evaluate their effects and to apply correction factors that would yield more accurate results.

Grout (1937) determined the effect of fragment shape in a test in which sized garnet and biotite were compared by weight percent composition and grain frequency, and he concluded that perhaps the platy minerals should be separated and weighed instead of counted. He also directed attention to the importance of the relative grain size of the minerals in computations of this type and concluded that procedures for this work should be standardized.

Chayes (1946), following the suggestion of Grout that flaky minerals be separated and weighed, has prepared a table showing average specific weights of some 15 mineral specimens compared to a specimen of beryl (from Acworth, N.H.) with an assumed value of 1. He also computed, using −100+200-mesh

[1] Publication authorized by the Director, U. S. Geological Survey.

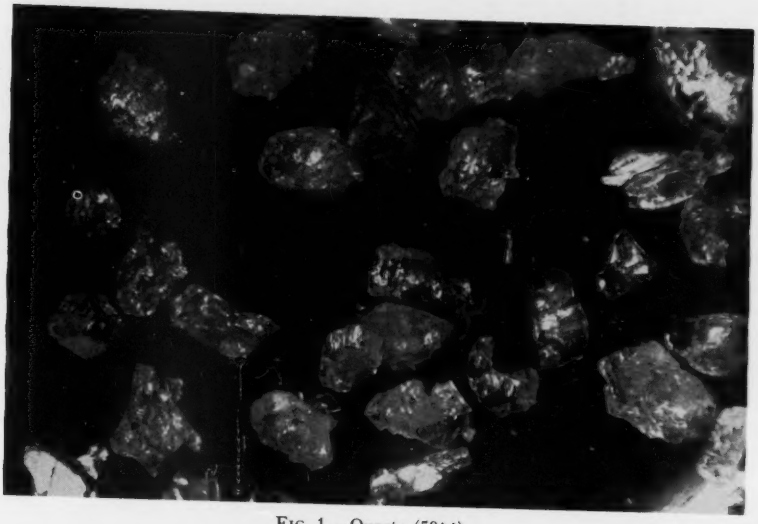

FIG. 1.—Quartz (50×).

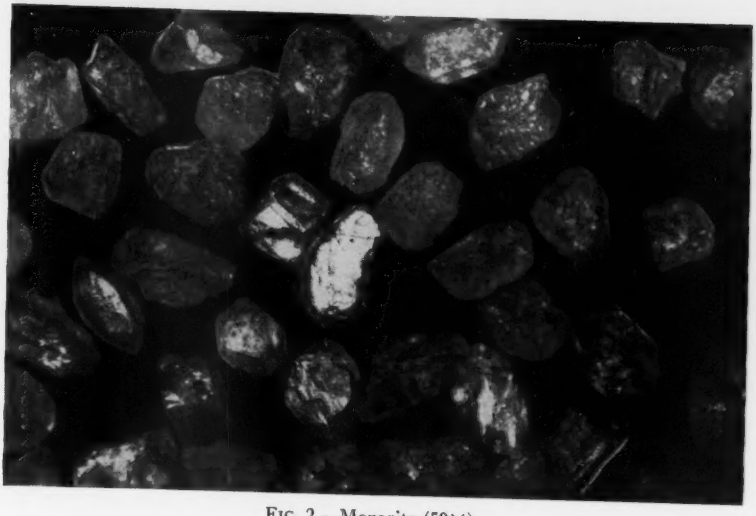

FIG. 2.—Monazite (50×).

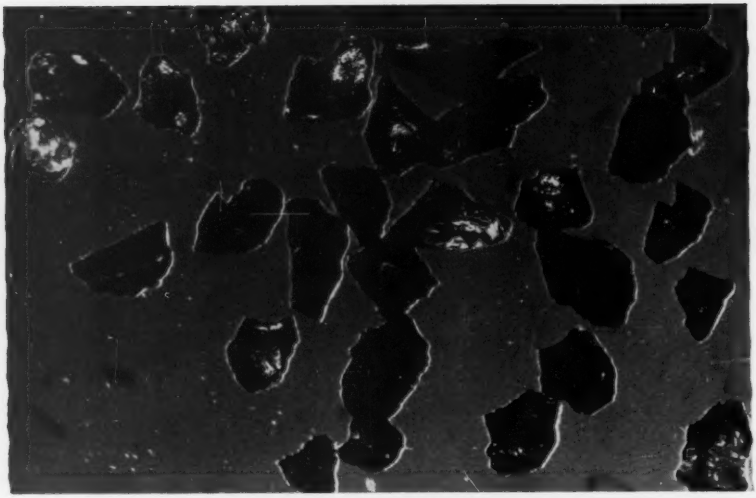

FIG. 3.—Ilmenite (50×).

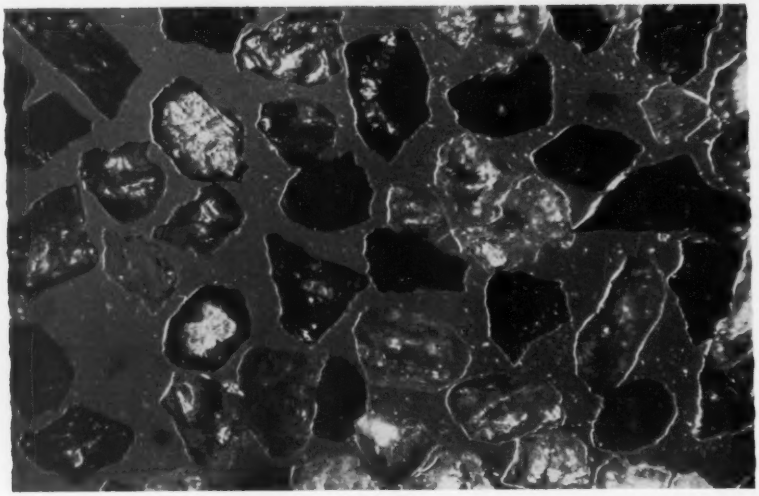

FIG. 4.—Mixture (50×).

material, apparent or average grain weights of calcite and muscovite in a series of mixtures of these two minerals.

Inspection of the sized samples used in the sample-splitting tests showed differences in the average size and shape of the three minerals. In view of these differences we have extended the idea of apparent grain weight proposed by Chayes using calcite and muscovite to granular minerals to minimize errors due to unknown shape and size factors.

GRAIN CHARACTERISTICS

To obtain the weight percent composition, grain counts or frequencies and densities are substituted in the equation, where F is the grain frequency and d is the specific gravity of the minerals.

$$(\text{Weight percent})_n = \frac{F_n d_n}{\sum_{i=1}^{n} (F_i d_i)}$$

The procedure for obtaining the grain frequencies may vary depending on the mesh size and the amount of sample to be counted, but in most cases it consists of counting for reasonable precision a minimum of approximately 300 grains (Dryden, 1931) from randomly selected fields of a mounted specimen. The specific gravity values assigned to each of the minerals are usually obtained from tables which list the specific gravity as an upper and lower limit. Grain frequencies, obtained by splitting samples of known weight percent by three different splitting methods are shown in table 2 of the previous paper.

Serious differences are possible between the actual mineral volume and the volume represented by the grain frequency. As the grain counts cannot be altered, correction for these differences must be made in the density factor of the equation and must include correction for specific gravity as well as for those mineral properties that influence volume. One factor of importance affecting the volume is the size distribution of the minerals within a mesh size. An inspection of the mineral grains shows that there are differences in shape and roundness from one mineral to another that would seriously influence any calculations based on the assumption of equal grain volume. The relative size, shape, and surface characteristics of the mineral grains used in the experiment are shown in the photomicrographs (figs. 1–4). Although the minerals were all sized to −80+100 mesh, it is apparent from the photographs that quartz displays embayments, ilmenite angularity, and the monazite grains are well rounded.

The size distributions of the quartz and ilmenite seem much wider than that of the monazite, and the average grain size of the latter appears much larger. It is incorrect, therefore, to assume that the minerals have equal grain volumes.

WEIGHTS PER GRAIN

To obviate the use of specific gravity and obtain the true weight relationship from the grain-frequency data, the average weight per grain for each mineral was determined experimentally and substituted for d in the equation above.

These values were obtained by counting and weighing approximately 600 grains of each mineral and dividing the weight by the grain count. Means and standard deviations of six such weighings for each mineral are shown in table 1. Weight percent compositions, using both the specific gravity factor and the concept of average weight per grain (W/G) are shown in table 2.

The qualitative conclusions that one can draw from figures 1–4 are confirmed by the data in table 1. The mineral hav-

TABLE 1.—*Average weights per grain of the test minerals*

Mineral	Mean (micrograms)	Standard deviation (micrograms)
Quartz	8.46	1.66
Ilmenite	17.36	0.83
Monazite	27.13	0.60

TABLE 2.—*Weight percent composition of raw data (table 1) calculated by both methods*

Weight	Split	Counter	Microsplit						Cone splitter						Hand-quartering					
			Q		I		M		Q		I		M		Q		I		M	
			S.G.	W/G	S.G.	W/G	S.G.	W/G	S.G.	W/G	S.G.	W/G	S.G.	W/G	S.G.	W/G	S.G.	W/G	S.G.	W/G
5 grams	1	A	22.7	17.4	27.0	23.4	50.3	59.2	25.4	20.9	43.4	40.4	31.2	39.3	21.2	16.9	41.2	37.1	37.6	45.9
		B	23.0	17.7	26.8	23.2	50.2	59.1	25.3	20.7	43.0	39.7	31.4	39.6	18.8	14.8	40.8	36.4	40.4	48.8
	2	A	24.0	19.4	42.4	38.9	33.5	41.7	25.5	20.8	41.9	38.6	32.6	40.6	28.4	23.2	37.7	34.7	33.8	42.1
		B	23.4	19.8	42.6	39.1	33.0	41.1	24.7	20.1	42.3	38.8	33.0	41.1	27.4	22.2	38.4	35.2	34.2	42.6
	3	A	23.1	18.9	46.3	42.8	30.6	38.3	25.1	20.4	42.1	38.7	32.8	40.9	24.2	19.6	41.2	37.7	34.6	42.7
		B	23.3	19.1	46.3	42.8	30.4	38.1	25.6	20.8	41.7	38.4	32.7	40.8	23.8	19.3	42.0	38.3	34.2	42.4
10 grams	1	A	14.0	11.2	52.2	47.3	33.8	41.5	24.1	19.9	47.2	43.9	26.9	36.2	24.5	20.0	44.5	41.2	30.9	38.7
		B	15.2	12.2	51.5	46.9	33.2	40.9	23.7	19.4	47.0	43.6	29.4	37.0	23.8	19.3	44.5	41.0	31.7	39.7
	2	A	15.0	11.9	47.4	42.2	37.6	45.9	27.0	22.0	40.3	37.2	32.4	40.8	23.1	19.6	43.9	39.8	33.0	40.6
		B	14.1	11.1	47.9	42.7	38.0	46.2	26.4	21.4	39.4	36.2	34.2	42.4	22.3	20.1	45.6	40.9	32.1	39.0
	3	A	18.7	14.9	44.9	40.5	36.4	44.6	23.5	19.2	45.6	42.2	30.9	38.6	28.8	21.0	43.9	42.9	27.3	36.1
		B	18.3	14.6	45.4	41.2	36.3	44.2	23.6	19.2	43.4	39.8	33.0	41.0	28.1	21.2	44.6	43.0	27.4	35.8
20 grams	1	A	23.4	18.3	34.6	27.9	45.0	53.8	27.2	22.4	42.6	39.6	30.2	38.0	22.4	18.3	47.2	43.6	30.4	38.1
		B	23.6	18.5	31.9	28.1	44.5	53.4	26.7	21.9	43.2	40.2	30.1	37.8	22.2	18.0	46.5	42.9	31.3	39.1
	2	A	21.7	17.4	41.0	37.0	37.3	45.6	36.2	30.8	39.8	40.1	24.0	31.1	30.3	25.0	38.8	36.4	28.3	36.8
		B	21.1	16.9	44.0	40.0	34.9	43.1	35.1	29.7	41.0	39.2	23.9	31.1	30.5	25.0	38.7	36.0	31.0	39.0
	3	A	24.4	19.9	44.6	41.2	31.0	38.9	30.9	25.4	37.8	35.2	31.2	39.4	30.2	24.9	35.6	33.8	27.9	35.6
		B	23.5	19.2	44.8	41.2	31.7	39.6	30.2	24.6	37.2	35.5	32.6	40.9	30.0	30.2	37.0	35.1	27.0	34.3

ing the lowest weight per grain—quartz—has the largest standard deviation, that is, considerable variation exists in the *particle sizes of the quartz as shown in* figure 1. Conversely, monazite (fig. 2), with the largest weight per grain, has the smallest standard deviation.

This dispersion of grain weights is even more outstanding if one calculates the percent coefficient of variation (100 × standard deviation/mean). Using the data in table 1 these coefficients are 20, 5, and 2 percent for quartz, ilmenite, and monazite, respectively. This variation is not too surprising if one considers the artificial nature of the sample. The quartz and ilmenite were crushed from coarser material and the monazite was separated from placer sands. Hence the monazite is much more rounded than the quartz and ilmenite.

Inspection of the weight percent compositions in table 2 shows some substantial differences between the values listed for the two methods of calculation. One may also note that for any mineral the value calculated using the average-weight-per-grain method is normally closer to the known composition by weight. This is better demonstrated by the grand means of each of the minerals calculated by both methods as shown in table 3.

The method of calculating weight percents from grain frequency data from test samples using average weights per grain results in a 24 percent increase in the reported weight percents for monazite compared to calculations using

TABLE 3.—*Comparison of means of weight percent of composition of test minerals*

Mineral	Known composition	Calculated by		Differences S.G.−W/G
		S.G.	W/G	
Quartz	20	24.70	20.13	4.57
Ilmenite	40	42.03	38.63	3.40
Monazite	40	33.22	41.28	−8.06
	100	99.95	100.04	

specific gravity factors. This study has been conducted using mineral grains in the size range −80+100 mesh. It would be logical to assume that weight percents calculated by both methods might differ to a greater degree if a wider size range were used.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 26, NO. 3, PP. 228–239
FIGS. 1–10, SEPTEMBER, 1956

ORGANIC SEDIMENTATION IN WARNBRO SOUND, WESTERN AUSTRALIA

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ABSTRACT

Warnbro Sound is a small marine embayment of restricted circulation. The lithofacies consist of calcareous sands and silts, derived from pelagic foraminifera, clastic molluskan debris, etc., but with no terrigenous material. The sedimentary cycle is thus self-generating. Organic carbon and total nitrogen measurements have been correlated with bathymetry and sediment particle size, to show that the fine material corresponds to the depths (up to 10 fathoms), where hydrogen sulphide is observed and high organic carbon and nitrogen are concentrated. Thus an organic reserve is being developed within a partly barred basin, the barrier to which is a porous calcarenite and sand bar (5 fathoms) which would act as a logical reservoir for any potential petroleum development.

LOCATION AND GEOLOGICAL SETTING

Warnbro Sound is situated about 20 miles south of Fremantle, Western Australia, and is an ideal example of a small scale marine barred basin, uncomplicated by terrigenous sedimentation. The sill depth is mostly less than 5 fathoms, and the basin center approaches 10 fathoms. The Sound measures approximately 2 by 4 miles. It is almost completely protected from the open sea by a line of sandstone reefs, the Murray Reefs (figs. 1 and 3). These are composed of eolian calcarenite or "eolianite" (Pleistocene dune limestone) planed down to sea-level. They extend northward and southward. To the north they continue as Penguin Island, Cape Peron, Garden Island, Carnac Island, and numerous reefs between these islands. A parallel line about 3 miles off shore due west of Warnbro Sound, the Five Fathom Bank, runs through Coventry Reef, and culminates in Rottnest Island to the north. A third line of consolidated dunes parallel to the other two lies to the east of Warnbro Sound and forms the eastern shore of Cockburn Sound outcropping at Case Point, Woodman Point, and Fremantle.

Warnbro Sound owes its present position to the primary control exerted by these old dune ridges. The inner shore of the sound is the youngest of a set of beach ridges which are truncated to the north by another series parallel to the Rockingham shore of Cockburn Sound. These ridges were built up when the sea-level was dropping from its early Recent stand about 10 feet higher than at present (Fairbridge, 1950). Thus Warnbro Sound appears to be a relatively youthful feature, being formerly a southern extension of Cockburn Sound.

Credence is lent to this hypothesis when one compares the topography of the two sounds. Cockburn Sound is a large basin-shaped depression with a uniform depth of 10 fathoms; Warnbro Sound has a very nearly flat bottom of 7 to 9 fathoms (profiles, fig. 2; also fig. 3). The present smooth floor of these basins appears to be a relict of a former lower sea-level (about 10 fathoms). When the sea-level was lower a series of large shallow lagoons were formed, extending from somewhere near Fremantle in the north for about 100 miles to the south. Calcareous dunes were built up along its eastern and western shores; these were consolidated and now form the Garden Island, Cape Peron-Murray Reef ridge and the Fremantle-Woodman Point-Case Point line of dunes respectively. The subsequent rise of sea-level has drowned the lagoons, while banks such as Success and Parmelia have been built across the

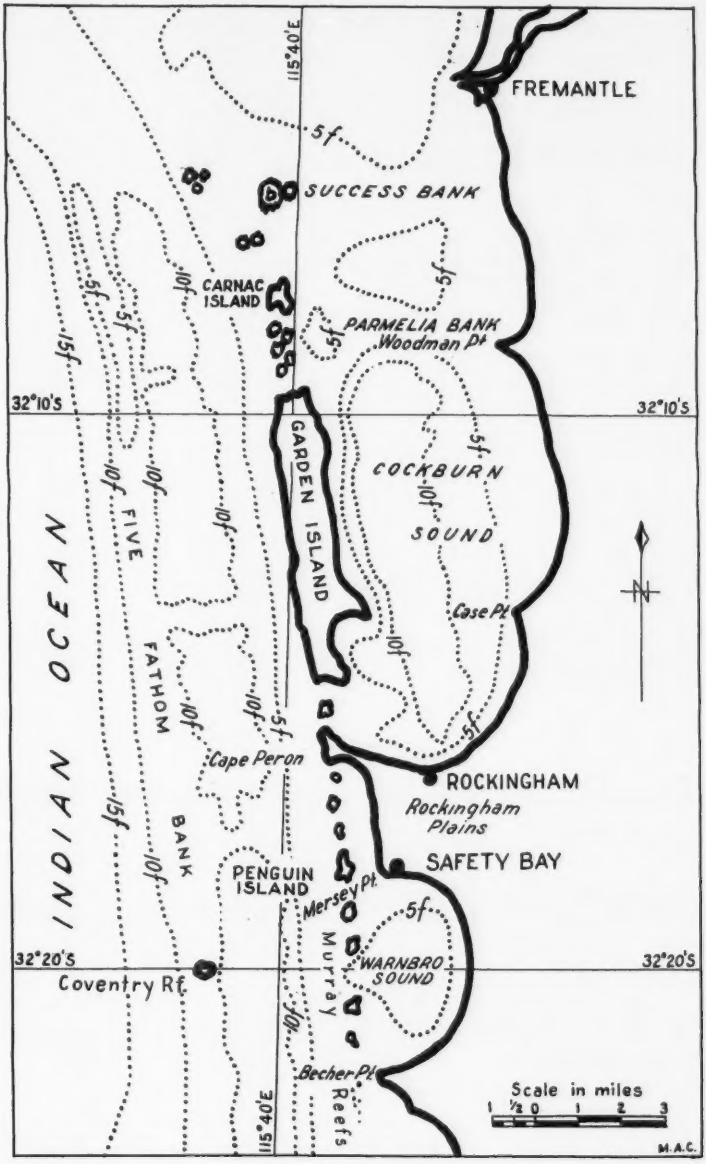

FIG. 1.—Map showing localities on southwestern coast of Australia which are mentioned in the text.

floor by wave refraction to enclose Cockburn Sound. Warnbro Sound had been cut off earlier by the Rockingham Plains, and tied to Cape Peron by a series of beach ridges, while sedimentation has made the resulting basin two fathoms shallower. Accordingly, the bottom deposit in Warnbro Sound is sandier than its Cockburn Sound equivalent. At Warnbro Sound two broad tongues of sand, the North, and the South sands (fig. 3) have been built up by a combination of wave refraction and longshore drift, leaving a channel 5 to 6 fathoms deep, Coasters Channel, between them. Both sand tongues appear to be in a state of dynamic equilibrium, balanced between a northward moving longshore drift in the summer, and a southward moving drift in the winter. They have been colonized and partly stabilized by the sea-grass (*Posidonia* spp.). Evidence of the sediment moving power of these drifts is given by Playford (1950) who has observed that a sand spit situated centrally on the east coast of Penguin Island (fig. 3) is hooked to the north in the summer and to the south in winter. These currents are controlled by the angle of incidence of the wave fronts, which in turn are controlled by the wind direction. An over-all movement of sand took place during the early part of the last century. The sound was surveyed then by J. S. Roe (1846), who records a harbor, Peel Harbour, as occurring there. This was separated from the main body of water by a scrub-covered narrow spit parallel to the eastern shore at the northern end of the sound. By 1846 this spit had entirely disappeared. There is no trace of it on the admiralty hydrographic chart based on a survey by Commander Archdeacon in 1878 (chart

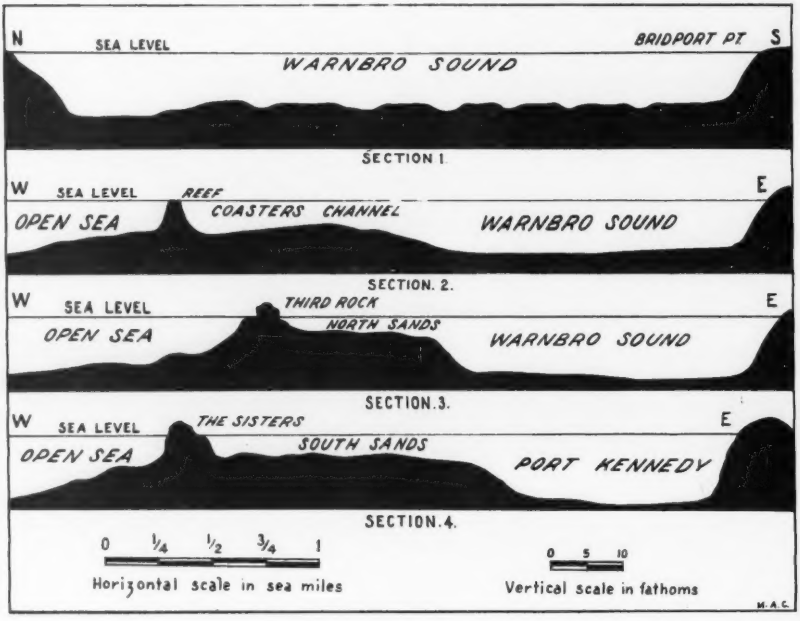

FIG. 2.—Profiles of Warnbro Sound. See figure 3 for location of sections.

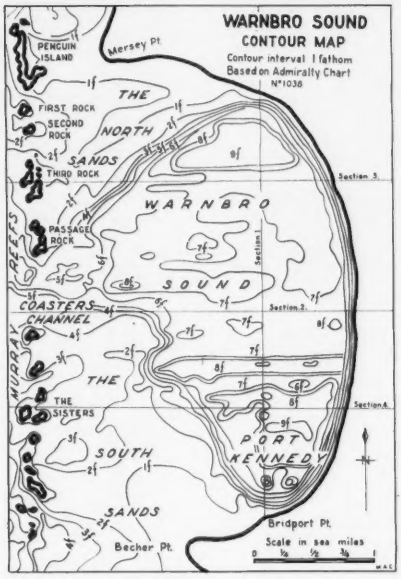

FIG. 3.—Bathymetric contour map of Warnbro Sound.

No. 1038). From the writer's observations and studies of aerial photographs, little, if any, change appears to have taken place, except that a few patches of clean sand are migrating across the sea-grass. A contour map of the sound has been prepared from the hydrographic chart (fig. 3).

HYDROLOGY

Although the seasonal hydrology of Warnbro Sound has not been investigated, work on the sediments suggests that the lower layers of the basin may stagnate at times, and some samples smelled strongly of hydrogen sulphide when they were collected. The basin is seen to be completely enclosed below a sill depth of 5 fathoms (fig. 3), and therefore it seems reasonable to expect that a thermal stratification would develop during summer, which would be broken down by the strong winter winds.

During the summer season (October to March) when air temperatures are high (100°F), light offshore winds are prevalent in the morning with calm seas. These are replaced in the evening by a light sea breeze which induces a moderate swell. The winter months are characterised by a series of low pressure systems which pass south of Australia. These cause strong northwesterly to westerly winds which cause rough seas during these months. There is little variation in the temperature of surface water which is maintained between 18 to 20°C throughout the year.

THE WARNBRO SOUND SEDIMENTS

Sampling Techniques and Laboratory Treatment of Samples

The field samples were taken with a "clam shell" snapper from R. V. *Lancelin* on 29th–30th November, 1951. They were collected on a grid pattern of half

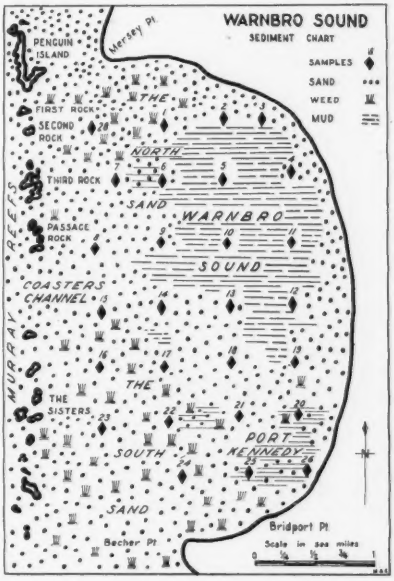

FIG. 4.—Sediment chart of Warnbro Sound showing lithofacies and sampling stations.

mile squares (fig. 4) so that a random sampling technique is approximated, enabling maps of the variation of the statistics of the sediments to be plotted. This technique has been adopted by Krumbein (1939) in a tidal lagoon environment with marked success, since it enables the relationships between sediment and the environment to be readily established. When a sufficient number of environments have been sampled in this way, standard sedimentary patterns will be established and will aid greatly in the interpretation of the deposits in the stratigraphic column.

The sampling stations and numbers are given in figure 4. Representatives of each type of sediment have been chosen from the analyses to illustrate each point. Mechanical analyses have been made of all samples, and "phi" median diameters, first and third quartiles, "phi" quartile deviation, and "phi" skewness have been calculated. Carbon and total nitrogen analyses have been made and are reported.

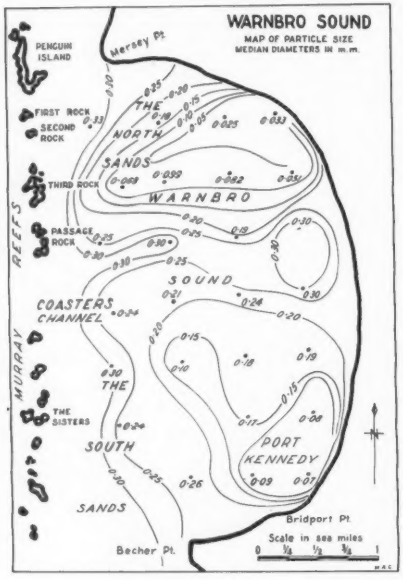

FIG. 5.—Map showing distribution of particle size in Warnbro Sound. Median diameters in millimeters.

Field Sampling Error

The field sampling error was of a high order. Under the best of conditions Krumbein (1934) estimated a field sampling error of at least eight times any errors introduced in the laboratory in a mechanical analysis. Rittenhouse and Connaughton (1944) verified Krumbein's estimates. The greatest error is introduced in the soft muds by the penetration of the sampler well into the mud before it closes. On the sands the fine materials are washed out as the sampler is pulled up through the water. The effect of these errors is felt primarily in the chemical analyses for organic carbon and total nitrogen. These errors must outweigh by many times any introduced in the laboratory. In view of this large field error it is gratifying to find that the analyses show a very uniform pattern. These indicate that the present conditions of sedimentation have been in progress long enough to form a reasonably thick deposit.

Mechanical Analyses

The mechanical analyses were made in the Geology Department of the University of Western Australia using standard Tyler sieves greater than 0.062 mm (Wentworth, 1922). For the finer-grained sediments, a modified pipette method was used as recommended by Krumbein (1932). The samples were first washed free of salt.

The results of the mechanical analyses have been plotted in the form of cumulative weight percentage curves against "phi" diameter. The "phi" measurements are easily convertible into millimeters by reference to the graphs of Krumbein (1939). Two typical curves, one for sand and one for mud are shown (fig. 9).

Cumulative weight percentage curves have been drawn for all the samples

collected and median diameter has been estimated in millimeters and its variation is mapped (fig. 5).

Chemical Analyses

Estimates of organic carbon content and total nitrogen were made by the writer in the hydrological laboratory of C.S.I.R.O. Federal Division of Fisheries, West Australian Station. The carbon analyses were made in duplicate on whole powdered samples, washed and dried at 105°C, using a modified technique (Walkley and Black, 1934). The results have been multiplied by a constant (in this case, 1.7) to give approximate organic carbon values. These results have been plotted in figure 6. The conversion factor used above is based on the assumption of approximately 58 percent recovery of the organic carbon present. This method of determining the organic carbon is based on a technique developed by Schollenberger (1928), who clearly recognized its limitations and the need for running parallel accurate combustion determinations on selected samples, and chose the conversion factor accordingly. During this series of analyses, equipment was not readily available for the necessary checks to be run. Therefore, the results are to be interpreted with due caution.

Allison (1935) has subsequently found that the heat of reaction in the Walkley and Black method does not reach the required minimum for accurate results. Trask and Patnode (1942) have enumerated four factors which influence the amount of chromic acid reduced in the above method:

1. The quantity of organic matter.
2. The state of oxidation of this organic matter.
3. The presence of oxidizable inorganic substances such as pyrite.
4. The extent to which the organic matter can be oxidized by the chromic acid under the conditions of analysis.

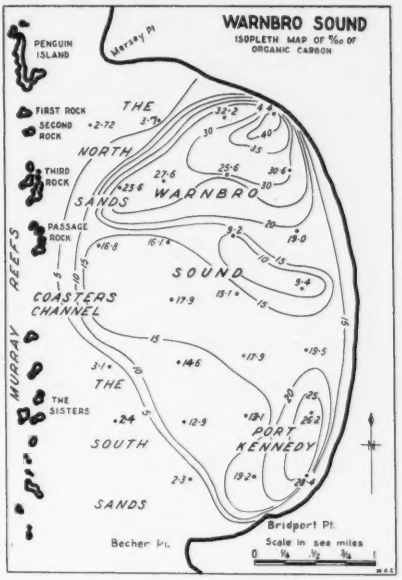

FIG. 6.—Isopleth map of organic carbon content of sediments in Warnbro Sound.

Experience in soil analysis has shown that negligible error is introduced by the modifying factors, but it should be remembered that pyrite is sometimes an abundant constituent of sedimentary rocks, is formed under stagnant basin conditions (Galliher, 1933; Strøm, 1939), and may introduce considerable error in the organic carbon content of the bottom deposits when this method is used. The state of oxidation of the organic matter must also be affected under these conditions. The bacterial populations in a black mud, and on a sand, would be physiologically distinct (Galliher, 1933). This could effect Trask's fourth factor.

Trask has used the term "reduction number," which is defined as the number of cubic centimeters of 0.4 N chromic acid which is reduced by 100 milligrams of sediment under certain standard conditions (Trask and Patnode, 1942, p. 41), and he gives methods of deter-

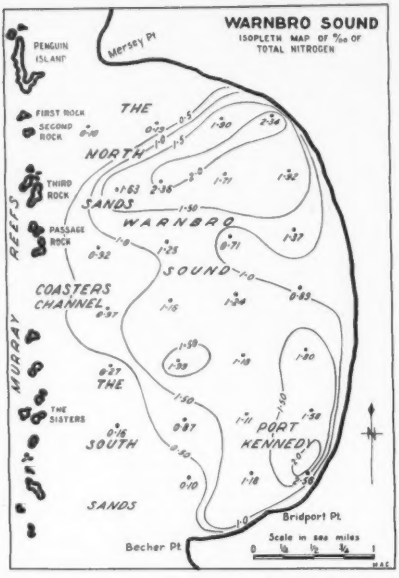

FIG. 7.—Isopleth map of total nitrogen content of sediments in Warnbro Sound.

mination (pp. 46–55). He has called the ratio of the carbon content to the reducing power the oxidation factor.

In the total nitrogen analyses the micro-Kjeldahl method was used. The procedure is outlined by Rochford (1951). The results of the analyses have been plotted (fig. 7).

The analyses for organic carbon and total nitrogen were combined in a map of the distribution of the C:N ratio (fig. 8). The results of the chemical and mechanical analyses are given (table 1).

Description of Bottom Sediment

Twenty-seven samples of the bottom sediments were collected during this survey. These represent the two major facies present. They are the clean sands colonized by sea grass deposited in shallow water and organic muds deposited in deeper water (fig. 9).

The nature of the constituents of these samples were analyzed in detail under a binocular microscope by classifying 300 particles selected from the material retained on each sieve during the mechanical analyses. The results given (table 2) are thus based on a count of at least 1800 particles from each sample and are considered to be fairly reliable. The outstanding feature of all samples is the predominance of particles of animal origin. It is evident, however, that the relative abundance of quartz grains is greater in the mud samples than in the sand. This could be explained by the slower rate of accumulation in the deeper protected waters of the basin proper allowing destruction of the softer calcareous particles by mud eating animals such as the irregular echinoids *Peronella leserui* and *Amblypneustes* spp. which are present in this area of the basin in large numbers.

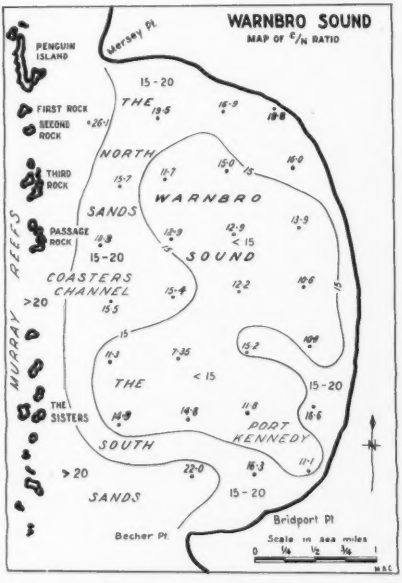

FIG. 8.—Map of Warnbro Sound showing distribution of *C/N* ratio in sediment.

TABLE 1.—*Statistics for Warnbro Sound samples*

Sample No.	Mdϕ	$Q_1\phi$	$Q_3\phi$	QDϕ	Skqϕ	C°/$_{oo}$	N°/$_{oo}$	C/N	Depth in fathoms
1	2.5	2.2	2.75	0.27	−0.025	3.7	0.19	19.5	1
2	5.3	4.5	6.0	0.75	−0.05	32.2	1.90	16.9	5.5
3	4.9	3.0	6.3	1.65	−0.25	44.0	2.34	18.8	7.0
4	4.1	2.7	5.1	1.20	−0.20	30.6	1.92	16.0	9.0
5	3.7	2.15	5.35	1.60	+0.05	25.6	1.71	15.0	9.0
6	3.4	1.8	5.0	1.60	0.00	27.6	2.36	11.7	7.0
7	3.9	2.7	4.8	1.05	−0.15	25.6	1.63	15.7	2.5
8	2.0	1.3	3.5	1.10	+0.40	16.8	0.92	18.3	5.0
9	1.8	1.1	3.3	1.10	+0.40	16.1	1.25	12.9	8.0
10	2.4	1.5	3.6	1.05	+0.15	9.2	0.71	12.9	7.0
11	1.8	1.9	3.5	0.80	+0.90	19.0	1.37	13.9	8.0
12	1.8	1.0	3.7	1.35	+0.55	9.4	0.89	10.6	8.0
13	2.1	1.2	3.4	1.10	+0.20	15.1	1.24	12.2	8.0
14	2.3	1.3	3.8	1.25	+0.25	17.9	1.16	15.4	7.0
15	2.1	1.0	3.3	1.15	+0.05	15.0	0.97	15.5	6.0
16	1.8	1.4	2.4	0.50	+0.10	3.06	0.27	11.3	3.0
17	3.3	2.05	4.45	1.20	−0.05	14.6	1.99	7.3	8.0
18	2.5	1.1	4.0	1.45	+0.05	17.9	1.18	15.2	7.0
19	2.4	1.1	4.3	1.60	+0.30	19.5	1.80	10.8	7.0
20	3.64	1.4	1.3	1.95	−0.29	26.2	1.58	16.6	8.0
21	2.60	0.8	4.1	1.65	−0.15	13.1	1.11	11.8	7.0
22	insufficient for mechanical analysis					12.9	0.87	14.8	2.5
23	2.1	1.65	2.45	0.40	−0.05	2.38	0.16	14.9	2.5
24	1.95	1.45	2.45	0.50	0.00	2.29	0.104	22.0	1.5
25	3.5	2.8	4.2	0.70	0.00	19.2	1.18	16.3	6.0
26	3.9	3.2	4.5	0.65	−0.05	28.4	2.56	11.1	6.0
27	No sample taken; sampling station inaccessible.								
28	1.6	1.3	1.9	0.30	0.00	2.72	0.104	26.1	3.0

Discussion of Test Results

Inspection of the maps of the sound showing the distribution of organic carbon (fig. 6), total nitrogen (fig. 7), and median diameter (fig. 5), indicates that their isopleths are related to the depth contours (fig. 3 and table 1); thus, the most important controlling factor seems to be the general topography. On the basin floor the particle size of the sediment is small, with the organic carbon and total nitrogen content high. In the sands, as would be expected, the organic carbon and total nitrogen are low, but the carbon to nitrogen ratio is highest. The carbon to nitrogen ratio appears to decrease, but not very uniformly, towards the center of the basin. The variation in this ratio is from 7.35 to 26.1. Also, it does not show the expected high values in the basins that it would if inorganic substances such as pyrite were reducing extra chromic acid in the organic carbon determinations. The high carbon to nitrogen ratio of the sands may be due to some constant error of analysis which increases in magnitude as the quantity of organic matter falls. This makes little difference to the isopleths of the organic carbon content, but can considerably alter the carbon to nitrogen ratio. Trask (1939) quotes an average carbon to nitrogen ratio of 10 with ranges mainly between 8 and 12 for recent marine sediments. Wiseman and Bennett (1940) found that this ratio is not constant in the bottom deposits of the Arabian Sea, but has a much greater variation than is admitted by Trask.

The carbon-nitrogen ratio has been plotted (fig. 6). When interpreting these results the words of Waksman (1933) should be borne in mind, "as in the case of soil formations, the humus of mineral soils varies considerably from that of

TABLE 2.—*Average composition of bottom deposits*

Classification of Constituents	Frequency						
	Sands					Muds	
	Sample No. 1	Sample No. 16	Sample No. 23	Sample No. 24	Sample No. 28	Sample No. 5	Sample No. 17
Mollusk fragments	26	33	34	40	39	67	38
Gastropod (whole)	< 1	< 1	—	1	—	1	1
Bryozoa	—	< 1	1	3	2	—	2
Echinoderm fragments	—	—	< 1	< 1	—	2	1
Foraminifera	27	2	< 1	< 1	< 1	2	2
Radiolaria	—	—	—	< 1	< 1	< 1	< 1
Sponge spicules	4	1	2	4	2	< 1	—
Fecal pellets	—	5	—	13	7	1	2
Unclassifiable particles of organic origin	37	51	56	35	41	12	35
Quartz grains	*5*	*7*	*6*	*3*	*8*	*14*	*18*
Total	100	100	100	100	100	100	100

forest soils and especially from that of peat bogs; one may also expect that the humus of mud bottoms should vary in chemical nature from that of sand bottoms and deep oceanic sediments as a result of difference in origin and decomposition processes."

Allowing for the difference between the large number of soundings on which the contour map is based (fig. 3) and the fewer samples analyzed in this study, a close correlation has been found between the topography and the statistics of the bottom sediment. Trask (1932) has already shown that, in the deep sea, the topography controls the organic content of the sediments which is highest in the basins and lowest on the ridges and sills. Krumbein (1939) in a study similar to the present one, established the relationship between high organic carbon content and fineness of the sediment in water of shallow depth in Barataria Bay, a part of the Mississippi delta.

GENERAL DISCUSSION

The environment can be classified as a marine littoral basin. Two dominant sedimentary facies are recognizable, the grey muds of the basin proper and the sands of the sill area (fig. 4). The characteristic feature of the sands is their organogenic nature, the only inorganic constituent being some well-rounded quartz grains seldom larger than 0.5 mm in diameter. These have been derived by marine erosion from the Pleistocene eolianites, which border the shore line along most of the West Australian coast. They are thus secondarily sorted and deposited by the present sedimentary regime.

The most abundant identifiable constituents are the shell fragments and, locally, foraminifera, the most conspicuous of which is *Marginopora vertebralis* (Blainville), which lives on the sea grass *Posidonia* spp. on the shallow tongue sands. In the larger grade sizes most fragments can be assigned without difficulty to one of the categories in the tables. In the finer grades, however, the number of unclassifiable constituents becomes relatively larger, indicating that the shell fragments and foraminifera are being broken down by wave action to form the unknowns in the finer grades. The sieving tends to separate the shells and fragments according to their normal growth size, and if one particular form is abundant, as is *Marginopora* in sample

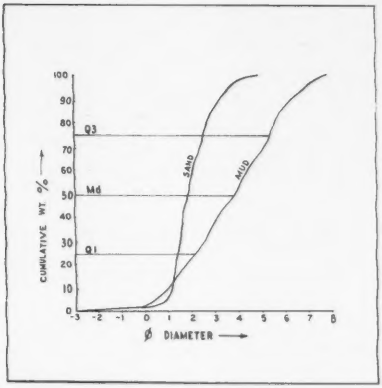

FIG. 9.—Cumulative weight percentage curves on "phi" scale of a selected sand and mud sample.

No. 1, it tends to dominate certain grade sizes.

In any study of recent sedimentation it is difficult to decide whether the shell fragments should be included in the mechanical analyses. Many workers disregard them altogether, dissolving them out and working solely on the insolubles, generally the quartz grains. In this paper the writer has adopted the alternative view that the organogenic fragments will be subjected to the same sedimentational forces as are the insolubles and they will in general be indicative of the environment of deposition, when they are acting as inert particles, i.e. after the death of the organism. All large intact shells that are believed to have died *in situ* and are too heavy to have been carried by currents and waves have been purposely excluded from the mechanical analyses; if preserved in a stratigraphical sequence these would be regarded as fossils. The isopleths of median diameter (fig. 5) closely follow the depth contours, and thus vindicate this procedure by establishing a positive relationship between sediment size and depth.

A summary of the statistics of these sediments is given in table 1. Most of the samples give symmetrical curves except for a few of the muds which show a moderate amount of skewness. The highest value for (Skq ϕ) is only +0.90. On the whole, the sands are well-sorted and show little spread; they grade through sandy muds to muds one of which has a QDϕ of 1.95. A typical sand and mud have been illustrated (fig. 9).

The environment of deposition could be correctly interpreted by following the standard practice of regarding coarse well-sorted sediments as indicative of shallow water, and the fine sediments as still or deep water deposits. But it should be realized that the depth did not exceed 10 fathoms and the surface waters of the sound are entirely continuous with the open ocean.

Modern petroleum geologists tend to regard the presence of fossil reefs and other bioherms as favorable sites for drilling. There are many similarities between the Warnbro Sound environment and the normal reef environment. The porous sands and core of eolianite on the seaward side would act as suitable reservoirs for any petroleum which might

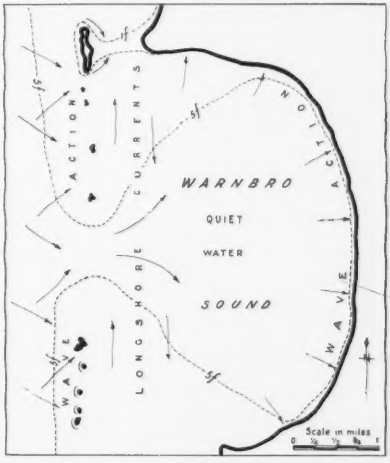

FIG. 10.—Diagrammatic illustration of forces active in producing the sedimentation pattern in Warnbro Sound.

ultimately be formed from the muds of the basin; analyses show the latter to be rich in organic carbon (table 1, fig. 6) and therefore potential source beds (Trask and Patnode, 1942).

Organic sedimentation of the type described in this paper has been observed to play a part in the localization of certain Lower Paleozoic sulphide ore bodies in the Bathurst District, New South Wales, Australia (Stanton, 1955).

CONCLUSIONS

In Warnbro Sound a self generating sedimentation cycle in equilibrium with the present sea-level has been developed, the sediment being derived from the destruction of the hard shelled invertebrates in the animal community structure. This source can only be maintained if excess sediment is removed by longshore drift or wave action. Thus while there is a continual and relatively rapid turnover of sedimentary particles, there is opportunity while this delicate equilibrium is maintained, for greatly enriching the deeper water sediments in organic matter thus forming potential source beds for petroleum or sites for sulphide mineralization when other factors are favorable.

ACKNOWLEDGEMENTS

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FIGS. 1–14, SEPTEMBER, 1956

PETROLOGY OF GYPSUM-ANHYDRITE DEPOSITS IN SOUTHWESTERN INDIANA[1]

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ABSTRACT

Crystalloblastic anhydrite, present in some dolomitic parts of the St. Louis limestone (Mississippian, Meramecian) in southwestern Indiana, is exemplified by two different textural associations: (1) gneissic porphyroblastic anhydrite in extensive lenticular beds, and (2) a later stage of porphyroblasts and veins formed penecontemporaneously with dolomite rhombs. Magnesium sulfate solutions acting upon calcium carbonate may have brought about the anhydrite-dolomite association. Magnesium ions, necessary to form the sulfate solution, may have been released from the gypsum lattice upon conversion to anhydrite or from some other sources.

Textural characteristics of the gypsum indicate that it was formed by hydration from recrystallized anhydrite. Although primary gypsum could not be recognized as such, much of the calcium sulfate was probably originally precipitated as gypsum.

For gypsification to take place, space must be available for water in addition to space occupied by anhydrite; this total volume (anhydrite plus water) is greater than the amount of space occupied by the resultant gypsum. Distortion of rocks may follow gypsification of anhydrite but is the result of directional forces exerted by crystals within gypsum veins rather than total volume expansion.

Results of X-ray studies indicate that hemihydrate is a rare mineral constituent of the Indiana deposits.

INTRODUCTION

Since the discovery and economic development of gypsum in Indiana, the Industrial Minerals Section of the Indiana Geological Survey has carried out an extensive investigation of the deposits. McGregor (1954) has concluded that these evaporites were deposited in intrasilled basins and that the depositional pattern reflects cyclic epeirogenic movement. As a correlative to his work, a study of the petrology of the evaporites was instigated. This investigation had as its prime purpose the determination of the processes that have taken place since the evaporite beds were deposited; it was based upon petrographic relationships, X-ray studies, and laboratory experiments.

The approximate extent of the evaporite area is shown in figure 1. Evaporite deposits are known to occur west of the area indicated on the map but are small in size. Figure 1 also shows the location of two diamond drill core holes. Two hundred thin and polished sections were prepared from the cores for petrologic study.

The evaporite deposits, consisting of lenticular gypsum and anhydrite beds, are in the lower part of the St. Louis limestone (Mississippian, Meramecian) at depths below the surface averaging 500 feet. Individual evaporite beds are variable in thickness but do not exceed 25 feet (Pinsak, oral communication, 1955). The uppermost beds consist almost entirely of gypsum; anhydrite increases in amount with increasing depth. Generally, three major evaporite beds are present, and each bed is separated vertically by 40 to 50 feet of limestone and dolomitic limestone which contain minor argillaceous bands.

Present studies indicate that the Indiana evaporite deposits have passed through at least three stages of diagenesis. It is suggested that at least the largest portion of the evaporites was

[1] Published by permission of the State Geologist, Indiana Geological Survey.

originally precipitated as gypsum. Later diagenesis resulted in the conversion of gypsum to anhydrite. Removal of overburden and exposure of the secondary anhydrite deposits to a new equilibrium condition permitted the formation of the present gypsum beds.

PETROLOGY OF ANHYDRITE

General Statement

Anhydrite in the Indiana evaporite deposits has been recrystallized. No evidence was found to indicate whether the present anhydrite was recrystallized from older anhydrite or from gypsum.

Two stages of crystaloblastic anhydrite which are exemplified by the following occurrences are evident:

Stage 1. *Gneissic porphyroblastic anhydrite* occurs in the largest amounts and includes extensive massive beds.

Stage 2. *Porphyroblasts and veins in dolomite* occur in minor quantities and are associated with dolomitization.

Gneissic Porphyroblastic Anhydrite (First Stage)

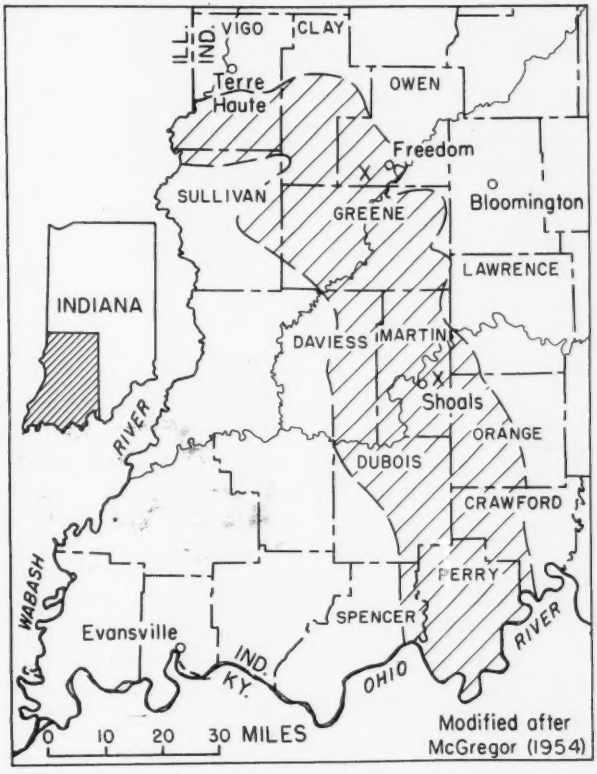

FIG. 1.—Map showing approximate areal distribution of evaporites in southwestern Indiana.

FIG. 2.—Gneissic anhydrite. Crossed nicols (×75).

The first stage of recrystallized anhydrite is characterized by a texture consisting of elongate crystals having both a subparallel and parallel orientation (fig. 2) interrupted sporadically by irregular to rectangular porphyroblasts (fig. 3). Local areas show a distinct spherulitic texture. Subparallel orientation grades into many different distorted flow patterns. Deviation from parallelism is attributed to carbonate bodies and other impurities.

Orienting forces for gneissic anhydrite are ascribed both to directed pressure caused by differences in rock strength and to stresses exerted by minor post-depositional adjustments of the earth's crust. Turner and Verhoogen (1951) have pointed out that pressure resulting from weight of overlying rocks is not entirely hydrostatic and some directed pressure may result from differences in the mechanical properties of the rocks. The gneissoid texture of anhydrite indicates that recrystallization probably took place after the evaporites had been covered by a large quantity of rock.

The mechanism by which anhydrite crystals have been oriented is believed by the author to be due to recrystallization flow. Griggs (1940) conducted experiments on flow of gypsum and showed that an inconsequential amount of deformation is produced in the absence of solution. The same specimen in its saturated soluton will flow at a relatively rapid rate. These experimental results indicate that a similar process (recrystallization flow) may have taken place in the formation of gneissic anhydrite.

The occurrence of porphyroblasts cannot be fully explained on the basis of recrystallization flow under directed stress alone. A possible explanation which is analagous to the recovery or elastic aftereffect observed in metals may be found. When stress is removed from some metals, a rebound or growth phenomenon has been noted because the metal is in a state of thermodynamic disequilibrium (Ramberg, 1952). Following the removal of stress on the evaporites centers within the gneissoid anhydrite body which respond most rapidly to conditions of thermodynamic stability may well be represented by porphyroblasts. The porphyroblasts, which are generally rectangular, are believed to be the most stable form thermodynamically under the new conditions of equilibrium.

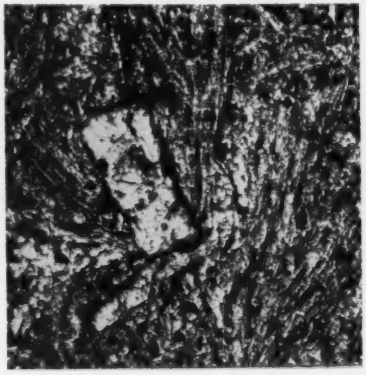

FIG. 3.—Gneissic anhydrite showing porphyroblasts. Crossed nicols (×75).

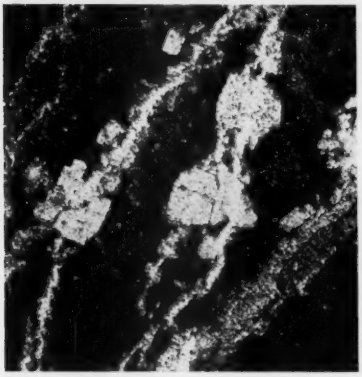

FIG. 4.—Anhydrite veins and porphyroblasts contained in dolomitic matrix. Crossed nicols (×25).

Anhydrite Porphyroblasts and Veins (Second Stage)

Anhydrite porphyroblasts and veins occur in minor quantities and are associated with dolomitization (fig. 4). This stage was initiated after much stress had been relieved, probably owing to removal of overburden. Translation gliding planes in grains within anhydrite veins (fig. 5), however, indicate that minor stresses were exerted. Bands, formed because of translation gliding, are extremely narrow which, according to Buerger (1945), is indicative of mild deformation.

Rhombohedra and rounded grains of dolomite occur in abundance adjacent to and within anhydrite veins and porphyroblasts and in the intervening carbonate matrix (fig. 6). The invariable association and apparent penecontemporaneous formation of dolomite with anhydrite porphyroblasts indicate that magnesium ions were abundant in solution at the time of formation of the second stage of anhydrite. Paragenetic relations indicate that dolomite continued to form after the crystallization of anhydrite (fig. 7). This observation is indicated both by peripheries of anhydrite which have been corroded by dolomite and by dolomite veins which are rarely present along anhydrite cleavages.

The source of the magnesium ions for the formation of dolomite is problematical, but at least three possible sources may be suggested.

1. Connate water would be a source of an appreciable quantity of magnesium (Clarke, 1924).

2. Solution of dolomite in overlying dolomitic formations furnishes an additional source for magnesium ions.

3. Magnesium ions may have been released from primary gypsum after its conversion to anhydrite.

Chemical analyses indicate that gypsum may accommodate considerably more magnesium in its structure than anhydrite (table 1). If one postulates that most of the originally precipitated material was gypsum (a possibility which will be considered later), the conversion of gypsum to anhydrite provides a source of magnesium.

Clarke (1924) has indicated that the action of magnesium sulfate solutions on limestone may result in the formation of calcium sulfate and dolomite. Petrographic evidence indicates that a similar reaction must have taken place in the

FIG. 5.—Translation gliding in grains in anhydrite veins. Crossed nicols (×75).

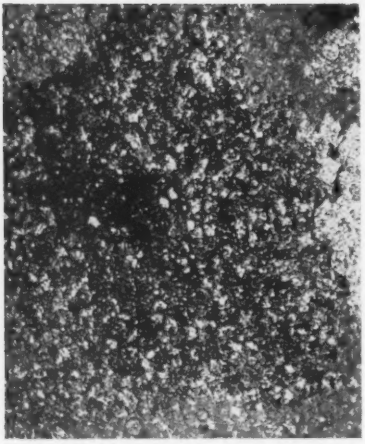

FIG. 6.—Rhombohedra and rounded grains of dolomite in anhydrite porphyroblasts and in adjacent carbonate matrix. Crossed nicols (×75).

Indiana deposits, although the mechanism of this reaction is uncertain. Theoretically this reaction should proceed spontaneously, as the solubilities of the products are less than those of the reactants. That this reaction is spontaneous can be shown by a calculation of the free energy of the reaction:

$$Mg^{++}SO_4^{=} + 2\,Ca^{++}CO_3 \xrightarrow[CO_2\ sat'd]{H_2O} Ca^{++}Mg^{++}(CO_3)_2^{=} + Ca^{++}SO_4^{=}.$$

Using the expression $\Delta F = -RT \ln Ka$ where Ka represents the equilibrium constant in terms of activity, the following calculation may be made:

$$\Delta F_1^\circ = -RT \ln \left(\frac{A_{CaMg(CO_3)_2} \cdot A_{CaSO_4}}{A_{MgSO_4} \cdot A^2_{CaCO_3}} \right)$$

$Ca^{++}Mg^{++}(CO_3)_2^{=} \rightarrow$ Dolomite

$$\Delta F_2^\circ = -RT \ln \frac{A_{dol.}}{A_{sol'n}}$$ (Free energy change of crystallization)

$$\Delta F^\circ = \Delta F_1^\circ + \Delta F_2^\circ = -RT \ln \left(\frac{A_{CaSO_4}}{A_{MgSO_4} \cdot A^2_{CaCO_3}} \right).$$

Since the activity $A = \gamma x$ where γ is the activity coefficient and χ is the mole fraction, then:

$$\Delta F^\circ = -RT \ln \left[\frac{(\gamma x)_{CaSO}}{(\gamma x)_{MgSO_4} \cdot (\gamma x)^2_{CaCO_3}} \right]$$

Values for activity coefficients were obtained from Taylor (1931), Kline (1929), and Frear and Johnson (1929). A maximum concentration was assumed for $CaCO_3$ (Comey and Hahn, 1921), and the concentration of the other components are in stoichiometric proportion:

$$\Delta F^\circ = -RT \ln \left[\frac{.69 \cdot 1.77 \cdot 10^{-4}}{.69 \cdot 1.77 \cdot 10^{-4}\ (.52)^2 (3.55 \cdot 10^{-4})^2} \right]$$

$\Delta F^\circ = -10.2$ K. cal/mole (25°C, 1 atm.).

The negative change in free energy −10.2 K. cal/mole indicates that the reaction will proceed spontaneously. It should be pointed out, however, that change in free energy does not indicate the kinetics of a reaction, but indicates only the stable phases under a given set of conditions.

TABLE 1.—*Magnesium content in Indiana gypsum and anhydrite core samples*[1]

Random Samples			
Gypsum (as $CaSO_4$)		Anhydrite	
Sample Number	Mg (in percent)	Sample Number	Mg (in percent)
1	.014	8	.008
2	.014	9	.001
3	.040	10	.014
4	.17	11	.093
5	.027	12	.090
6	.074	13	.034
7	.035	14	.016
Samples taken in adjacent positions across transition zone			
15	.17	15A	.044
16	.027	16A	.023
17	.107	17A	.033
Average	.0678	Average	.0356

[1] Analyzed by R. F. Conley and R. K. Leininger, 1955.

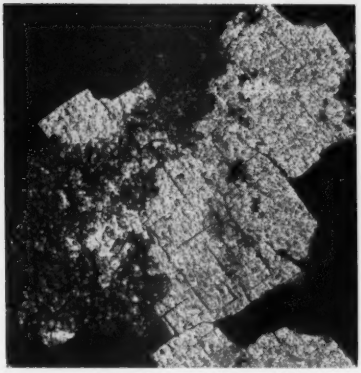

FIG. 7.—Penetration of anhydrite porphyroblast by dolomite mass. Crossed nicols (×75).

PETROLOGY OF GYPSUM

General Statement

Gypsum in the Indiana deposits has formed from the hydration of anhydrite. This process of hydration began after removal of much overburden and exposure of anhydrite to near surface conditions. Thermodynamically gypsum is the most stable calcium sulfate phase in the presence of pure water below 40° C (Kelly, Southard and Anderson, 1941). Gypsification presumably proceeds along zones of weakness by solution of anhydrite and subsequent precipitation as gypsum. Incipient gypsification occurs most commonly along contacts of evaporites with carbonate rocks. From this initial stage, hydration continues along fractures, pseudocubic cleavage in anhydrite, and crystal boundaries.

Textures Indicative of Secondary Gypsum

Textural relations provide the most important evidence that all present gypsum is secondary. Textures most diagnostic of secondary gypsum are:

1. Automorphic outlines of gypsum against anhydrite (fig. 8) show that gypsum has replaced anhydrite. Gypsum crystals that are within anhydrite and that are isolated from other gypsum crystals develop the most perfect crystal outlines and occur in the largest amount at the immediate front of gypsification.

2. Relict anhydrite grains are included within gypsum crystals (fig. 9) and are most abundant near the transition zone. For the most part, relict grains consist of porphyroblasts which originally existed in the gneissic anhydrite.

3. Abundant gypsum veins associated with anhydrite show that anhydrite has been taken into solution and then precipitated as gypsum (fig. 10).

4. Well-developed flow structures are not present in gypsum, as would be expected if it had been buried to a comparable depth as anhydrite.

Additional evidence for the secondary nature of the gypsum is indicated by the present depth of the evaporites (average 500 feet), relative abundance of ground water, and lack of abundant dissolved salts. Such conditions of temperature and salinity are favorable to the formation of gypsum (Kelly, Southard, and Anderson, 1941). Thus, gypsification of anhydrite represents the tendency to achieve equilibrium in the existing environment.

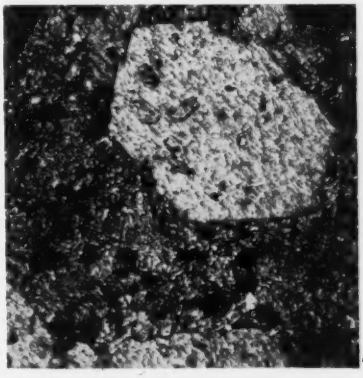

FIG. 8.—Euhedral gypsum crystals in anhydrite. Note relict anhydrite crystals in gypsum. Crossed nicols (×75).

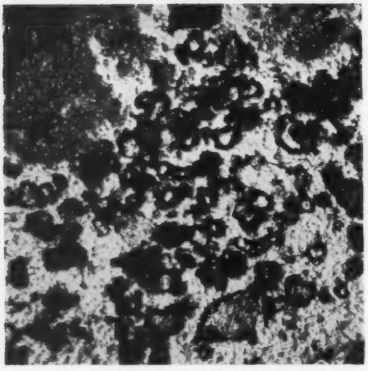

FIG. 9.—Relict anhydrite grains in gypsum. Dark outlines represent replacement by carbonate. Crossed nicols (×75).

Volume Expansion

The alteration of anhydrite to gypsum involves an increase in volume of 30 to 50 percent (Pettijohn, 1949). Figure 11 illustrates this volume relation in which the unit cell of gypsum has been superimposed on the unit cell of anhydrite. Each of the unit cells contains 4 molecules. The unit cell of anhydrite has been determined by Wasastjerna and that of gypsum by Wooster (Bragg, 1937).

In recent papers volume expansion due to hydration has been accounted for by the removal of calcium sulfate in order to preserve the original volume of the rock (McGregor, 1948; Goldman, 1952; and Goodman, 1952). Distortion of rocks because of volume expansion has been accounted for by a separate crystallization force due to the growth of gypsum crystals. Desch (1914), however, does not postulate a separate crystallization force but suggests that vector properties in crystals, because of cohesive forces, act more strongly in certain crystallographic directions. He illustrates crystallization force by an experiment in which a test tube is partly filled with water and plaster of Paris. Following hydration of the plaster of Paris, the test tube in many of these experiments breaks owing to apparent expansion. The reaction is:

$$CaSO_4 \cdot \tfrac{1}{2}H_2O + 1\tfrac{1}{2}H_2O \rightarrow CaSO_4 \cdot 2H_2O$$

When it is realized that a 7 percent decrease in volume follows the completion of the reaction, the breaking of the test tube may seem to be anomalous. This result, however, serves to illustrate directional forces exerted by crystal growth although an over-all decrease in volume occurs.

Farnsworth (1924), in her study of volume relations of gypsum and anhydrite, shows that 1000 gm of gypsum occupy a volume of 431 cc and the equivalent amount of anhydrite and water occupies a volume of 473 cc. Thus, gypsum occupies about 9 percent less volume than the equivalent amount of anhydrite and water. Figure 12 shows this volume relationship.

The discussion above therefore shows that for gypsification of anhydrite to

FIG. 10.—Massive gypsum and gypsum veins in carbonate matrix. The gypsum was derived from the gypsification of anhydrite. Crossed nicols (×25).

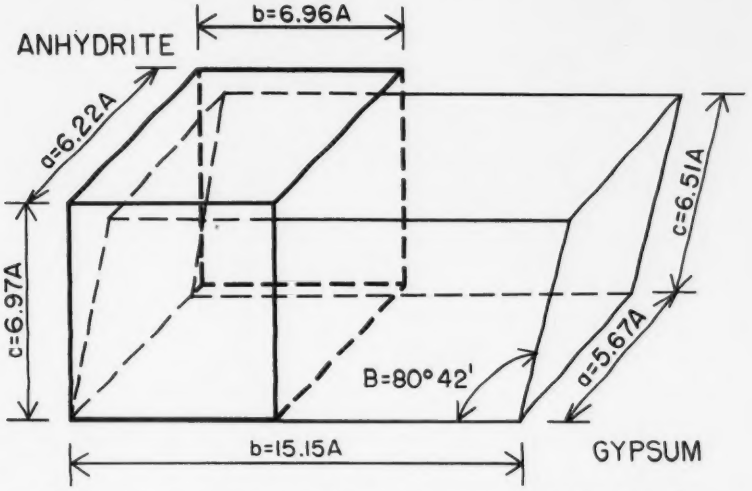

FIG. 11.—Volume comparison of unit cells of gypsum and anhydrite. Data after W. L. Bragg, 1937.

take place space must be available for water in addition to the space occupied by the anhydrite. A given body of anhydrite upon altering to gypsum will not occupy a greater volume than the original anhydrite and requisite water. The requisite amount of space for ground water circulation may be attained through solution of peripheral areas of the anhydrite body and subsequent removal of the $Ca^{++}+SO_4$=solution to other parts of the adjacent rock. Evidence that this solution process has taken place is furnished by the large amount of gypsum veins associated with the gypsification of anhydrite. Figure 10 illustrates this association and also shows that the transverse structure of the veins terminates abruptly at the massive gypsum. This relationship is indicative of the penecontemporaneousness of vein formation with the gypsification of anhydrite. Figure 10 also shows that the increased volume of the solid phases is accounted for by vein formation.

Growth of Gypsum Veins

The most probable mechanism for providing of space for the growth of transverse gypsum veins has been the separation of vein walls through forces exerted by directional crystal growth. These forces were directed normal to the vein walls and their effects are illustrated by a three-dimensional view in figure 13. From this illustration it can be seen that the inclusion in the vein was derived from the re-entrant in the vein wall and that only vertical components of force were involved in its displacement. This same relationship can be seen in many gypsum veins.

The method of growth of cross-fiber veins has been explained by Schmidt (Buckley, 1951). He believes that solutions saturated with calcium sulfate were supplied by capillary openings normal to a plane of weakness. Solutions move to the plane by capillary attraction, and a crystal, once started, continues to grow at the junction of the vein wall and the gypsum crystal. The crystals are thin

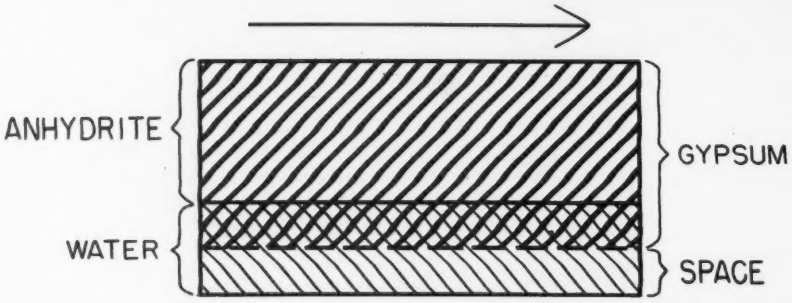

FIG. 12.—Volume relations of the reaction: $CaSO_4+2H_2O \rightarrow CaSO_4 \cdot 2H_2O$.

and fragile but are able to support tremendous weight because of close grouping.

Taber (1918) came to the same conclusion as Schmidt as a result of both field and laboratory observation. He found relatively small transverse crystals in veins formed in fine-grained rocks and large transverse crystals in coarse-grained rocks. This observation further substantiates supply of solutions through capillary openings.

Separation of vein walls by growth of gypsum crystals may at first appear to be contradictory to Riecke's principle (Ramberg, 1952). Taber (1918), however, points out that crystals will continue to grow, even when opposed by external forces, provided that the faces under pressure remain in contact with a supersaturated solution. Solutions from which the gypsum is precipitated presumably are derived from anhydrite. When the solutions become saturated with respect to anhydrite they are, therefore, supersaturated with respect to gypsum (Kelly, Southhard, and Anderson, 1941). These conditions are then consistent with the provision pointed out by Taber.

The formation of cross-fiber veins can neither be explained adequately by the filling of primary spaces nor attributed to replacement processes. Evidence that cross-fiber veins did not grow into an open space is the absence of banding or crustification. In addition, the crystals interfinger irregularly, and median lines within veins are absent. When one wall of a vein contains irregularities, corresponding irregularities in the opposite wall are such that the two surfaces would fit closely if placed in contact. This vein wall relation would not be expected if replacement processes had been active.

An additional possibility is that transverse gypsum veins have altered directly from transverse anhydrite veins as believed by Goldman (1952). This possibility cannot be substantiated in the Indiana deposits for the following reasons:

1. Anhydrite veins contain randomly oriented anhydrite crystals.

2. Transverse gypsum veins do not contain relict anhydrite crystals, and they do not grade into anhydrite veins.

3. Gypsum veins are found in large quantities only in areas where gypsification of anhydrite has obviously taken place. The calcium sulfate which supplied the gypsum veins must have been derived from the anhydrite. Anhydrite bodies which have not been subjected to gypsification are rarely associated with veins.

In the above discussion volume expansion is expressed in the evaporite sequence only by the separation of gypsum-vein walls. The evidence in-

dicates, therefore, that distortion of rock beds associated with gypsum does not occur as a direct result of volume expansion but is brought about by directional forces exerted by crystals within abundant gypsum veins.

Occurrence of Hemihydrate in Indiana Evaporites

Results of X-ray studies indicate that hemihydrate ($CaSO_4 \cdot \frac{1}{2}H_2O$) is a rare mineral constituent of the Indiana deposits. The only other reported natural occurrence of hemihydrate is in hot arid sections of Turkmenia and Fergana (Popov and Vorobiev, 1947), where it has been found as thin layers in petroleum-bearing sands. Its occurrence is attributed to the fact that dissociation pressure of gypsum is greater than the atmospheric vapor pressure.

Hemihydrate in Indiana was found by examining rock slices with an X-ray spectrometer. The rock slices were cut with a hacksaw to keep pressure on the mineral grains at a minimum. Five of the 25 slices of gypsum and anhydrite that were examined contained hemihydrate.

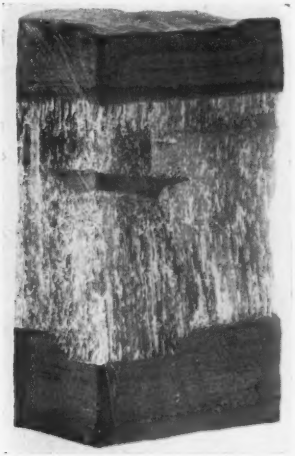

Fig. 13.—Gypsum vein showing displacement of inclusion (×1.5).

Its occurrence is apparently limited to the transition zone of anhydrite to gypsum. Figure 14 shows a single trace for a rock slice across an anhydrite to gypsum transition zone. The curve shows two of the most intense reflections for hemihydrate. Absence of many weak reflections is believed to be caused by coarseness of grain and lack of random orientation of hemihydrate within the rock slices. Figure 14 also shows a composite of traces from four rock slices that indicates weak reflections obtained from other traces.

The limitation of hemihydrate to the transition zone is indicative of its instability. The instability of hemihydrate in the absence of available water may be represented by the disproportionation reaction (Kelly, Southard, and Anderson, 1941):

$$4CaSO_4 \cdot \tfrac{1}{2}H_2O \rightarrow CaSO_4 \cdot 2H_2O + 3CaSO_4 \text{ (insoluble)}.$$

Because this reaction is very slow, hemihydrate formed in nature might well be expected to remain as a metastable phase over reasonably long periods of time. This assumes that conditions for formation of hemihydrate persist.

Two suggestions may be made to explain the occurrence of hemihydrate in Indiana. The first, which would be somewhat fortuitous, depends upon the release of NaCl and other salts during the gypsification of anhydrite. These released salts may form solutions of sufficient concentration, and consequently lower vapor pressure, to enable the newly formed gypsum to dissociate.

A second and more likely mechanism of dissociation is related to directed crystal growth of gypsum and the resultant directed pressure. This directed pressure may drive the water out of the pre-existing gypsum. Laboratory experiments indicate that hemihydrate may be formed from gypsum subjected to high pressures (Leininger and Conley, oral communication, 1955).

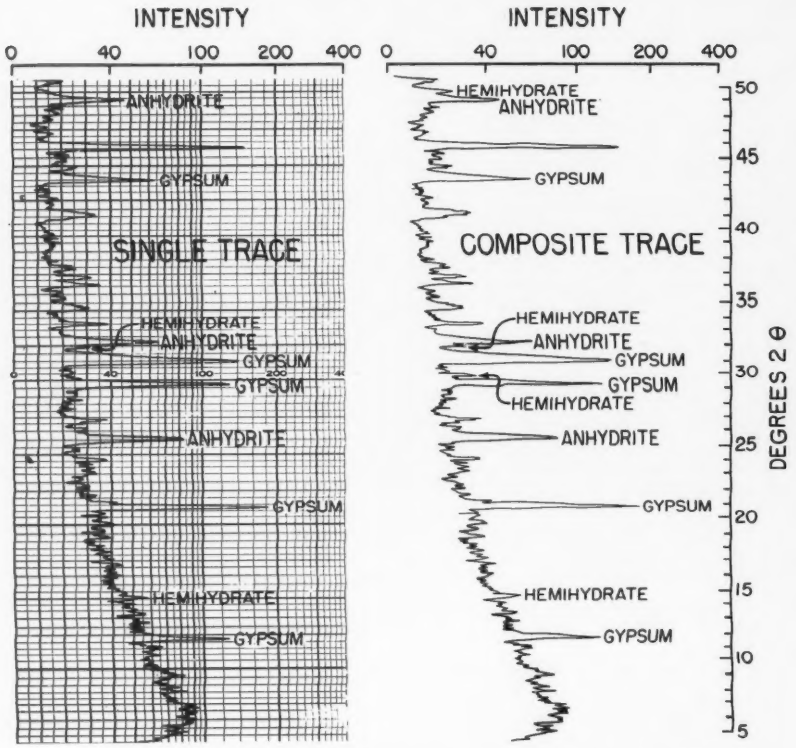

FIG. 14.—X-ray spectrometer traces showing naturally occurring calcium sulfate phases.

Problem of Genesis of Gypsum and Anhydrite

Petrographic observations do not indicate the presence or former presence of primary gypsum; however, it is believed that all evaporites were not deposited originally as anhydrite. Petrographic evidence does show that the present gypsum is secondary and that anhydrite has been recrystallized and, strictly speaking, cannot be considered as primary.

According to Pettijohn (1949), geological evidence indicates that the original material of most gypsum beds was anhydrite. The observation that gypsum beds at outcrop grade into anhydrite at depth and textural relations which indicate that gypsum is formed later than anhydrite support this view. This view also can be applied to the Indiana deposits in general; however, it cannot be considered as being rigidly consistent with petrographic evidence and with the present known stability conditions of the system $CaSO_4-H_2O$.

More recent opinions have favored the primary deposition of gypsum as well as of anhydrite. Stewart (1953), in his

study of the Permian evaporites of northeastern England, found pseudomorphs of anhydrite after gypsum at an approximate depth of 3800 feet. These pseudomorphs occur in definite beds and alternate with anhydrite beds that do not contain pseudomorphs.

Known conditions of gypsum and anhydrite stability also indicate that not all anhydrite is primary. From a study of solubility relationships, Posnjak (1940) has shown that the solubility curve of gypsum intersects that of anhydrite at approximately 4.8 times the normal salinity of sea water. This relationship holds at 30° C, and a difference in temperature of ±15° C will not greatly affect the solubility. Thus, at 30° C gypsum is the stable phase up to the above-mentioned concentration of salts, and above this concentration of salts anhydrite is the stable phase. Posnjak states that gypsum begins precipitating at 3.35 times the normal salinity of sea water. It is evident, therefore, that gypsum must always be deposited first when evaporation takes place below the transition temperature (42° C) of gypsum-anhydrite in a solution saturated with calcium sulfate.

Posnjak (1938) also has shown that gypsum in contact with saturated calcium sulfate solutions between 42° C and 97.5° C represents a metastable system, and, if anhydrite nuclei are not present, may persist indefinitely. This metastability field of gypsum, along with the condition that anhydrite nuclei must be present for the transition of gypsum to anhydrite, prevents a complete understanding of the system $CaSO_4-H_2O$ and the formation of its phases in nature.

A further complication was introduced by an experiment carried out by Leininger and Conley (oral communication, 1955). They first prepared a solution which simulated normal sea water composition as given by Posnjak (1940). Then the solution was allowed to evaporate at 60° C over a period of 3 weeks. Anhydrite, the stable phase to be expected under these conditions, was not produced and large crystals of gypsum were precipitated.

The petrographic observations that both anhydrite and gypsum are secondary and the laboratory evidence indicate that gypsum may be the predominant or only form of calcium sulfate precipitated from sea water.

It is further suggested that anhydrite does not form until after burial, at which time gypsum is converted to anhydrite because of increased temperature and pressure and subjection to interstitial solutions containing large amounts of dissolved salts. These conditions and time may be the additional factors necessary to overcome the energy barrier standing between metastable gypsum and the stable anhydrite phase.

SUMMARY

Gneissic porphyroblastic anhydrite occurs in extensive massive beds, and its texture is interpreted to be the result of directed pressures exerted by overburden and post-depositional adjustments of the earth's crust.

A second stage of anhydrite, present as porphyroblasts and veins, probably formed as a result of the action of magnesium sulfate solutions on calcium carbonate. This relationship is indicated by the invariable association of second stage anhydrite with dolomite rhombohedra.

Gypsum is believed to be secondary as indicated by textural relationships. For gypsification to take place, space must be available for water in addition to space occupied by anhydrite; the total volume (anhydrite plus water) is greater than the amount of space occupied by the resultant gypsum. Distortion of rocks may follow gypsification of anhydrite as the result of directional forces exerted by crystals within gypsum veins rather than total volume expansion.

X-ray diffraction analysis indicates that hemihydrate may occur naturally in the Indiana deposits at the transition zone of anhydrite to gypsum. Dissocia-

tion pressure apparently is of sufficient intensity to form hemihydate when gypsum is subjected to directed pressures as the result of directional crystal growth and when gypsum is present in salt solutions of high concentration.

Laboratory and petrographic evidence show that gypsum is the major primary form of calcium sulfate. Anhydrite, with time, is formed extensively only after burial.

ACKNOWLEDGMENTS

Experimental work and assistance in interpretation of many fundamental problems by Richard K. Leininger and Robert F. Conley of the Geochemistry Section, Indiana Geological Survey, were invaluable to this petrologic study. The writer also wishes to express his gratitude to Dr. Haydn H. Murrary and Dr. Duncan J. McGregor for their advice and criticism.

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FIGS. 1–5, SEPTEMBER, 1956

AN INTRAFORMATIONAL CONGLOMERATE BY MIXED SEDIMENTATION IN THE UPPER CRETACEOUS OF THE ROC-DE-CHÈRE, AUTOCHTHONOUS CHAINS OF HIGH SAVOY, FRANCE[1]

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AND
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ABSTRACT

The glauconitic and sandy limestone sequence, which in most places represents the Upper Cretaceous transgression throughout the High Calcareous Alps of the High Savoy, gives way in the Roc-de-Chère region to a 3- to 4-feet bed of conglomerate containing curiously shaped pebbles of fine-grained limestone scattered in a glauconitic matrix.

Three distinct limestone types may be distinguished in the conglomerate on the basis of shape, dimension, and induced flow structures (from base to top): (1) contorted streaks, (2) larger irregular pebbles with highly deformed matrix inclusions, and (3) still larger subrectangular chunks with slightly deformed matrix inclusions.

Well-developed flow structures are shown by the orientation of quartz grains and by the arrangement of deformed *Globotruncana* tests in both the pebbles and the matrix.

A tentative explanation might suggest a mixed sedimentation in which beds of plastic calcareous muds and glauconitic sands were alternately deposited. Reworking phenomena intensively stretched and mixed the freshly deposited beds. However, intensity of deformation decreases upward as depth of water increased during transgression.

Such a sediment may be classified as a special type of intraformational conglomerate formed under wave action when beds were still plastic.

INTRODUCTION

In the autochthonous chains of High Savoy, glauconitic detrital sedimentation began during Aptian times and reached its maximum during the Albian. The latter appears at the Roc-de-Chère as light-green, littoral facies, which is coarse-grained and almost devoid of fossils. The Albian sequence reaches a thickness of 65 feet; it consists mostly of glauconitic sands and sandstones rich in heavy minerals, and shows a small amount of calcareous matrix. Well-developed cross-bedding reveals deltaic conditions and explains why this facies is usually called "Albian molasse" (Paréjas, 1938).

Scarcity of fossils in the light-green sandstones must be attributed to the highly agitated conditions of sedimentation. However, fossils, especially ammonites, are abundant in the Albian black facies deposited toward the center of the basin. (Carozzi, 1951).

The origin of the detrital minerals of the light-green sandstones must be sought in the Hercynian crystalline massif of Belledonne situated 20 km toward the southeast which was undergoing active erosion. Indeed, toward the southeast the sandstones become coarser and grade into microconglomerates containing pebbles of vein-quartz reaching 8 mm in diameter.

LITHOLOGIC DESCRIPTION

The Cenomanian transgression following the Middle Cretaceous (Vorgosau) tectonic phases of the alpine folding marks the end of the clastic sedimentation. The latter is followed by a general subsidence leading to the deposition of fine-grained pelagic limestone which lasted through the entire Upper Cretace-

[1] Presented at the GSA annual meeting, New Orleans, Louisiana, November, 1955.

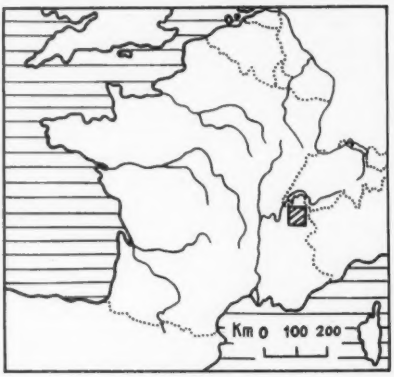

FIG. 1.—Map of France showing location of the area studied.

ous sequence. However, green sandstone sedimentation did not stop abruptly; the first calcareous deposits were actually sandy and glauconitic limestones which locally contain phosphatic nodules. This facies grades upward into lithographic limestones almost devoid of clastic minerals. Generally speaking, this transition zone, which is 15 feet thick, occurred during Cenomanian times. (Moret, 1926, 1934). However, in the Roc-de-Chère region (fig. 1), light-green sandstone deposition lasted through most of the Cenomanian; thus the transition zone is represented only by a relatively thin layer (3 to 4 feet thick), the aspect of which is very strange.

This transitional layer has no definite upper and lower boundaries; it gradually merges upward into the fine-grained limestone and downward into the glauconitic sands. It gives in the field a first impression of a conglomerate in which curiously shaped pebbles of fine-grained limestone are embedded in a glauconitic matrix. The relative proportion of pebbles rapidly increases upward, whereas that of the matrix decreases; however, the fine-grained limestone always contains scattered quartz and glauconite grains.

From the bottom to the top the following characters may be observed. First, in the upper portion of the cross-bedded glauconitic sands, highly contorted limestone streaks appear (fig. 2). They seem to be closely related to extremely irregular limestone pebbles which are located on top of them. The pebbles show deep matrix penetrations and extend along stretched apophyses far into the matrix. The apophyses may connect two pebbles or they may connect one pebble with some of the highly contorted streaks already described (fig. 3).

Many pebbles show completely isolated matrix inclusions with irregularly shaped boundaries; some inclusions seem to have been highly folded. In the upper part of the layer, one can see relatively large sub-rectangular pebbles (fig. 4). This somewhat regular aspect, in spite of the fact that it may be extremely irregular in detail, suggests that we have to deal with beds 1.0 to 1.5 inches thick, almost broken in place. In their lower part, irregular apophyses may connect them with the irregularly shaped pebbles and the contorted streaks situated just below

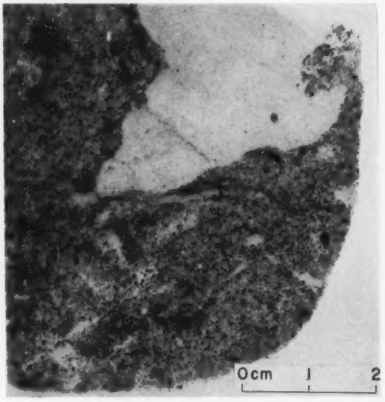

FIG. 2.—Polished surface normal to the bedding showing the bottom portion of the conglomerate. The highly contorted limestone streaks in the lower part of the picture are overlain by an irregular limestone pebble showing isolated matrix inclusions.

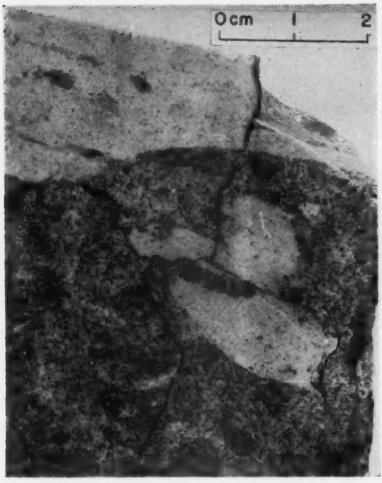

FIG. 3.—Polished surface normal to the bedding showing the median portion of the conglomerate. Irregular limestone pebbles are partially connected to one another by apophyses. They also show deep penetrations and numerous streaky inclusions of the sandy matrix.

These sub-rectangular elements contain thin sandy interstratifications. Some of them seem to have kept their original position, but most are highly contorted and even show whirl-like structures.

These layers of sub-rectangular pebbles are separated from each other by irregular and discontinuous sandstone strata. The thickness of the latter diminishes upward, while the limestone pebbles grade into nodular beds and finally into massive limestone.

To sum up, we observe in the field that the shapes of the pebbles become more and more regular while the calcareous sedimentation becomes dominant. Actually the most irregularly shaped elements are the streaks which occur on top of the cross-bedded glauconitic sandstones. A complete independence is obvious between the types of deformations shown by the different types of observed pebbles (streaks, irregularly shaped pebbles, and sub-rectangular chunks). This observation seems to us of the utmost genetic importance.

Microscopic observations enable us to go farther into the mechanics of formation of this strange conglomerate. The matrix appears as a glauconitic and micaceous sandstone which, however, has a larger proportion of limestone than the typical sandstones of the underlying Albian.

The streaks of fine-grained limestone and the irregularly shaped pebbles show *flow structures* which are well-developed throughout. These structures are clearly shown by the attitude of the *Globotruncana*, *Globigerina*, and ostracod tests as well as by the linear arrangement of the sponge spicules and *Inoceramus* prisms.

In the sub-rectangular pebbles the flow-structures appear to be irregularly distributed; they are well-represented in

FIG. 4.—Polished surface normal to the bedding showing the upper portion of the conglomerate. A large and complex sub-rectangular pebble covers most of the picture. It reveals highly contorted interstratifications displaying whirl-like structures.

the marginal parts of the pebbles, but in their central portions they may be recognized only when sandy lenses have been highly contorted and folded. In this case, true whirl-like structures corresponding to the arrangement of the microfossils, which follow exactly the same trend as those traced by the arrangement of the mineral grains, may be easily identified. Structures made up of the arrangement of *Lagena* tests are rare because of their nearly equidimensional character.

The matrix and the sandy inclusions in the limestone pebbles also show well-developed flow structures, but owing to the coarser character of the sand, these structures are displayed in a different way. Linear arrangement of the elongate quartz and glauconite grains are very suggestive; moreover, *Globotruncana* tests not only show similar behavior but have been frequently deformed and broken between large quartz grains. Such microscopic observations lead to the conclusion that the two types of sediments have been mixed together while in a very plastic condition.

DISCUSSION

The transitional layer bears a microfauna of Lower Turonian age. It appears entirely different from a usual conglomerate. Its formation occurred through a very peculiar submarine process which we will try to analyze.

Limestone pebbles and matrix are to the same age. The conglomerate they constitute corresponds to a well-known transgression. We can also state that the glauconite sands were deposited in highly agitated conditions, whereas the limestone was laid down in a quiet realm. However, scattered quartz and glauconite grains in the limestone pebbles show that the arrival of clastic material never entirely stopped.

The study of the transitional zone shows that if particular factors had not been active, it would have been made up of alternating beds of limestone and sandstone (fig. 5, G). The deformation processes were active, with a decreasing intensity upward, only during the deposition of the most important sand beds which are interbedded between the lime-

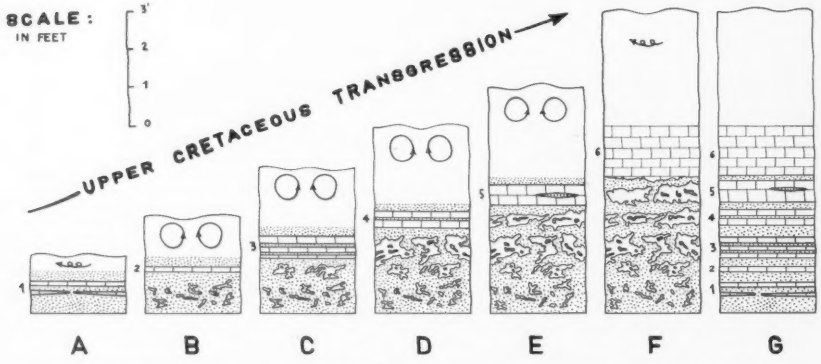

FIG. 5.—Diagrammatic sketches showing the successive phases of development of the Roc-de-Chère intraformational conglomerate.

Sketches A to F correspond to the deposition of the main sandy beds just before their being reworked with accompanying deformation of their limestone intercalations.

Circles with arrows symbolize wave-action and curled arrows indicate current-action.

Sketch G shows the inferred succession of sandy and limestone beds if no reworking had occurred.

stone strata. No sliding phenomena nor horizontal displacement could be located. The general aspect of the pebbles and especially that of the streaks suggests oscillatory movements which may be attributed to wave-action in shallow waters.

The mechanics may be described as follows: on top of the first limestone layers were deposited layers of glauconitic sand formed under agitated conditions. Oscillatory movements of the waves led to the reworking of the sandy mass and its still plastic limestone layers. The latter were mixed with the sandy matrix, stretched in irregular streaks and thus flow structures were formed in both components (fig. 5, A and B).

The deposition of the following limestone layers marks the return to periods of quiet separated by times when the sand beds were deposited and reworked. In this case, the relative proportion of limy and sandy components was nearly the same; curiously shaped pebbles were formed in which reciprocal inclusions were developed in the most striking manner (fig. 5, C). It is obvious that during each reworking the underlying deposits might have been secondarily affected.

Upward, the reworking shows a clear diminution of intensity as well as an intermittent character. Limestone layers were formed which contained thin sandy intercalations during the deposition of which no important deformation occurred. The latter took only place during the deposition of the last and most important sand layers. Consequently, subrectangular pebbles were formed with rapidly varying internal deformations (fig. 5, D and E). These pebbles are the less deformed elements of the whole conglomerate as the process neared its end because of increasing depth.

CONCLUSIONS

In conclusion, we are dealing with a peculiar type of intraformational conglomerate. Generally speaking (Carozzi, 1953), such rocks are formed by submarine processes acting on rapidly consolidated sediments. In the present case, the sediments were still in a plastic state and were reworked by shallow agitated water at the beginning of a well-known transgression.

ACKNOWLEDGMENTS

The writer wishes to thank Professor Ed. A. Paréjas, University of Geneva, for permission to describe this peculiar conglomerate which he first discovered in the field in 1926. He is also indebted to his colleagues Professor H. R. Wanless and Professor J. L. Hough for constructive criticisms.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 26, NO. 3, PP. 258–267
FIGS. 1–3, SEPTEMBER, 1956

THE TESNUS FORMATION OF TRANS-PECOS TEXAS

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ABSTRACT

Field and laboratory investigations indicate a twofold division of the Tesnus formation. The lower unit is marine and consists chiefly of siliceous shales and massive low-rank graywackes; the clay-mineral fractions of these rocks are composed mainly of illite and a mixed-layer chlorite-vermiculite. The upper unit is predominantly nonmarine and consists of fine-grained clastic sediments, mainly bentonitic platy shales and cherty shales in which illite and montmorillonite are the clay fraction.

INTRODUCTION

The Tesnus formation of Pennsylvanian age varies greatly in color, texture, and thickness from place to place in the region in which it is exposed. These variations present an interesting problem open to sediment-petrographic analysis. Athough they appear at first sight to be of random distribution, they have proved to be of systematic distribution and permit a refinement of the stratigraphy of this formation.

The well-known Tesnus formation crops out extensively in the Marathon uplift, but lesser outcrops can be found also in the Solitario dome and at Persimmon Gap in the Big Bend National Park. The formation was first studied and named by Baker and Bowman (1917). It is regarded as the oldest formation of Pennsylvanian age in trans-Pecos Texas (King, 1937). It is composed chiefly of fine-grained detrital sediments, shales and sandstones, apparently laid down under eugeosynclinal conditions (Kay, 1947; Krumbein and Sloss, 1951).

The thickness of the Tesnus formation varies, it ranges from about 6800 feet in the southeastern part of the Marathon uplift to about 300 feet in the northwestern part. Such a remarkable change within a distance of twenty-four miles seems to show that while the Tesnus formation was being deposited there was rapid subsidence and rapid deposition in the southeastern part, but that in the northwest deposition must have been slow, indicating the presence of a stable shelf area in the vicinity.

FIELD AND LABORATORY WORK

During the past six years the senior author has had the opportunity to investigate all the Tesnus exposures of the Marathon uplift while he was in charge of the summer field camp of the University of Houston Geology Department, which is located at Marathon in Brewster County. Field study has been extended also into the less-known outcrop areas of the Solitario dome and at Persimmon Gap, which are located southwest and south from the Marathon uplift (fig. 1). It was soon realized that the problem could not be solved satisfactorily through field study alone; therefore, samples were collected systematically and studied in the laboratory.

All the outcrops of the Tesnus were investigated in the field. Both lateral and vertical changes in texture, composition, thickness, and color were recorded. The changes which occur in a northeast-southwest direction were found to be of minor importance. On the other hand, the changes which show up along the southeast-northwest trend were found to be significant.

Twenty-eight representative samples of both shale and sandstone were col-

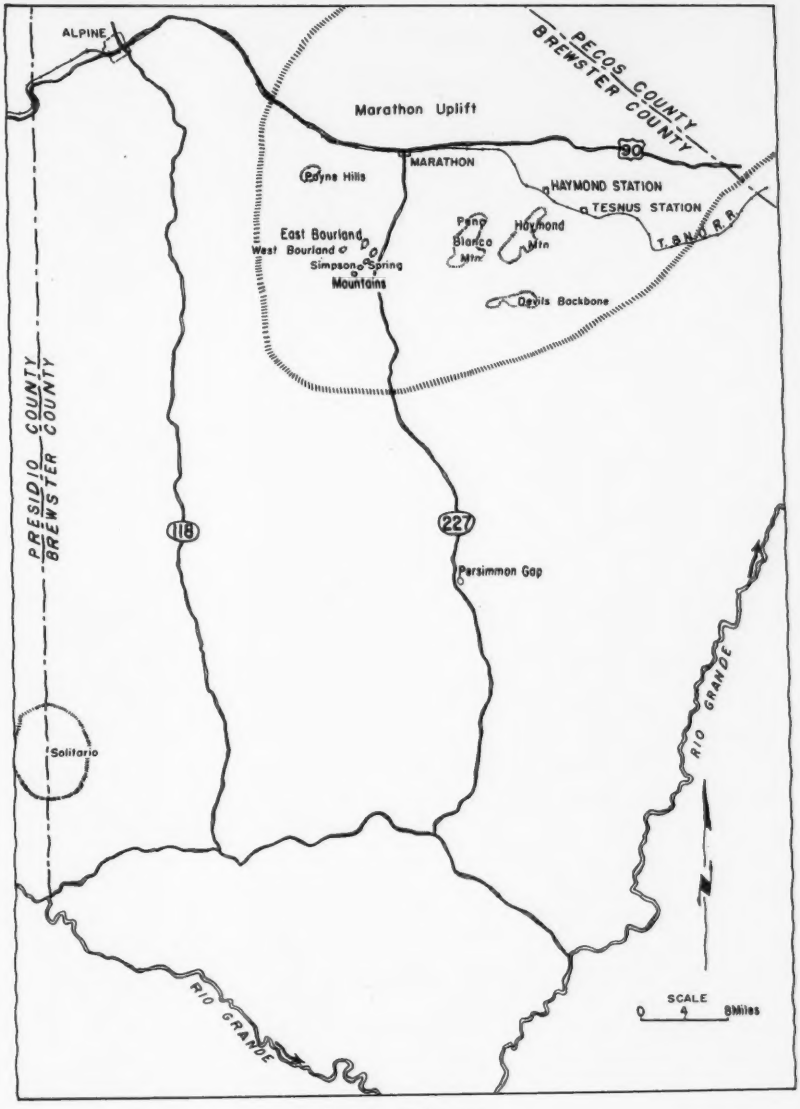

FIG. 1.—Index map.

TABLE 1.—*Color, percental composition, and median diameter of quartz grains in 15 samples of the Tesnus formation at location (1) between Pena Blanca and Haymond Mountains*

Sample Number	Rock	Color	Composition in percent		Median Diameter in mm
DIMPLE LIMESTONE—*overlying*					
UPPER TESNUS					
28	Shale	gray	illite montmorillonite		—
27	Shale	gray	illite montmorillonite		—
LOWER TESNUS					
26	Sandstone	buff	quartz matrix rock frag. chert feldspar	70–75 20–25 3 1 <1	.151
25	Sandstone	gray-green	quartz matrix feldspar rock frag.	60–65 25–30 2– 3 1	.124
24	Shale		illite chlorite- vermiculite		—
23	Sandstone	gray-green	quartz matrix rock frag. feldspar	60–65 30–35 5 <1	.080
22	Sandstone	gray-green	quartz matrick feldspar chert rock frag.	75–80 20–25 2– 3 1 1	.139
21	Sandstone	gray-green	quartz matrix rock frag. feldspar	75–80 20–25 1 <1	.172
20	Sandstone	buff-yellow	quartz matrix rock frag. feldspar	60–65 30–35 2– 3 <1	.087
19	Sandstone	gray-green	quartz matrix feldspar rock frag.	60–65 30–35 2– 3 1	.079
18	Sandstone	drab	quartz matrix feldspar rock frag.	70–75 20–25 2– 3 2	.069

TABLE 1—(*continued*)

Sample Number	Rock	Color	Composition in percent		Median Diameter in mm.
17	Sandstone	gray-green	quartz matrix rock frag. feldspar	55–60 35–40 2 <1	.075
16	Sandstone	gray-green	quartz matrix feldspar rock frag.	65–70 20–25 3 1	.112
15	Shale	gray-green	illite chlorite-vermiculite		—
14	Shale	gray-green	illite chlorite-vermiculite		—

CABALLOS NOVACULITE—underlying

lected in the field for laboratory study. Textural and heavy-mineral assemblage determinations were made on all the sandstone samples, and X-ray analyses were made on all the shale samples.

Textural Analysis

Because of the fact that all the sandstones are well lithified, the grain sizes could not be determined by mechanical analysis and thin sections had to be used. From 225 to 400 grains in each of the thin sections were measured by using a micrometer eyepiece mounted on a petrographic microscope; the median grain diameters were computed using Krumbein's (1935) method for calculating moments of measured grains. Sorting and degree of rounding were estimated from the thin sections.

The approximate percental composition of each sandstone was determined in order that these rocks might be classified precisely as to their individual tectonic environment.

In tables 1–3, the amount of quartz present in the sandstones is shown to range from 55 to 80 percent of volume. The shape of the quartz grains is predominantly subangular, but a few rounded grains are present. The matrix ranges from 20 to 40 percent of volume. This percental distribution indicates a moderate sorting for all the sandstones studied. In addition, a small amount of rock fragments is also encountered; the feldspar makes up less than 3 percent of the volume of the rock in every thin section studied. All the thin sections studied demonstrate that the sandstones fall into Krynine's (1948) "low-rank graywacke" or Pettijohn's (1949) "subgraywacke."

Clay Mineral Analysis

The shale samples selected for X-ray analysis were disaggregated to pass an 80-mesh sieve and dispersed in distilled water. The clay fraction of a size of less than 2 microns was separated by centrifuging. Ammonium hydroxide (1 N) was added to aid peptization. The samples, after drying at 35° C, were placed in a North American Phillips geiger-counter X-ray diffractometer and the diffraction patterns were obtained. They were treated with ethylene glycol, as needed, using a method which utilizes

TABLE 2.—*Color, percental composition, and median diameter of quartz grains in 9 samples of the Tesnus formation at location (2) between East Bourland and West Bourland mountains*

Sample Number	Rock	Color	Composition in percent		Median Diameter in mm.
DIMPLE LIMESTONE—overlying					
UPPER TESNUS					
13	Shale	gray-black	illite montmorillonite kaolinite		—
12	Shale	gray-black	illite montmorillonite		—
11	Chert	black	—		—
LOWER TESNUS					
10	Sandstone	gray-green	quartz matrix rock frag. feldspar	60–65 30–35 2– 3 <1	.119
9	Shale	green-blue	illite chlorite- vermiculite		—
8	Sandstone	gray-green	quartz matrix rock frag. feldspar	65–70 25–30 3 <1	.154
7	Sandstone	gray-green	quartz matrix rock frag. feldspar	60–65 30–35 2 <1	.115
6	Sandstone	gray-green	quartz matrix rock frag. feldspar	60–65 30–35 2 <1	.113
5	Shale	gray-green	illite chlorite- vermiculite		—
CABALLOS NOVACULITE—underlying					

the vapor pressure of ethylene glycol at low temperature (Brunton, 1955).

The thirteen shale samples analyzed are extremely siliceous, and therefore the clay fraction is somewhat masked by the large amount of very fine, angular quartz grains. The shales seem to fall into two compositional types (table 1–3; fig. 2): the type in which the clay constituents are illite and mixed-layer chlorite-vermiculite (as shown by sample 1, 2, 5, 9, 14, 15, 24) and the type that contains illite and montmorillonite (as represented by sample 3, 4, 12, 13, 27 and 28). All samples of the first type came either from the lower or middle part of the formation, but all samples collected from the upper part of the Tesnus formation show the second type of composition.

Heavy-Mineral Analysis

In order to separate the heavy-mineral assemblages, the sandstone samples were

TABLE 3.—*Color and composition of 4 samples of the Tesnus formation at location (3) two miles southwest of Payne Hills*

Sample Number	Rock	Color	Composition
DIMPLE LIMESTONE—overlying			
UPPER TESNUS			
4	Shale	gray-drab	illite montmorillonite
3	Shale	gray-drab	illite montmorillonite
LOWER TESNUS			
2	Shale	gray-drab	illite chlorite-vermiculite
1	Shale	—	illite chlorite-vermiculite
CABALLOS NOVACULITE—underlying			

crushed in a steel mortar and sieved, retaining that portion which passed through the 100-mesh but remained on the 150-mesh screen. Bromoform was used as the separating liquid. Approximately 0.1 to 0.5 percent by weight of heavy minerals was recovered from each sample. The heavy-mineral suites were examined under petrographic and binocular microscopes. The heavy minerals were classified by inspection as abundant, frequent, scarce, and rare. The result is presented in table 4.

Table 4 shows that magnetite and zircon are the most abundant of the heavy minerals. Biotite, tourmaline, hornblende, and augite are present too, but in smaller amounts and less persistently. Garnet is rare and is found in only three of the fourteen samples studied. Most of the heavy minerals are either euhedral or subeuhedral. Those having a round to subround shape constitute a very minor amount. The lack of abrasion and attrition on the surface of the overwhelming majority of the quartz grains seems to indicate that the lower Tesnus sediments were derived mostly from the weathering and erosion of igneous rocks which were probably cropping out not far from the site of deposition of the Tesnus sediments.

DISCUSSION

The Tesnus formation is essentially a medium-fine to fine-grained detrital sedimentary deposit laid down under eugeosynclinal conditions (Kay, 1947; Krumbein and Sloss, 1951). It can be divided into a lower marine member and an upper nonmarine member.

Lower Part of Tesnus Formation

The Paleozoic formations cropping

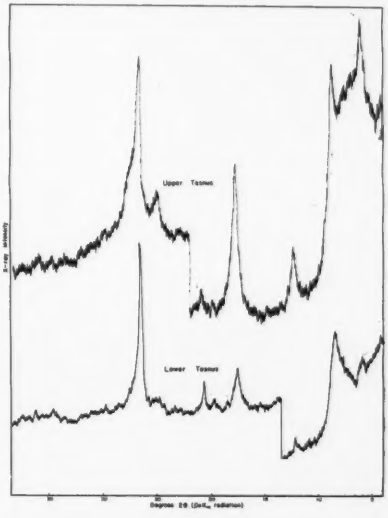

FIG. 2.—X-ray diffractometer patterns of minus two micron fraction of Tesnus oriented on glass slides.

TABLE 4.—*Heavy minerals from the Tesnus formation*

Sample	Magnetite	Zircon	Biotite	Tourmaline	Augite	Hornblende	Garnet
26	Abund.	Freq.	Scarce	Rare	—	—	—
25	Abund.	Freq.	Scarce	Rare	Scarce	Rare	—
23	Abund.	Abund.	Rare	Scarce	Rare	Scarce	Rare
22	Abund.	Freq.	Freq.	—	Rare	Rare	—
21	Abund.	Freq.	Scarce	—	—	Rare	—
20	Abund.	Abund.	Scarce	Scarce	Scarce	Rare	Scarce
19	Abund.	Freq.	Freq.	Scarce	Scarce	Rare	Rare
18	Freq.	Abund.	Rare	Scarce	—	—	—
17	Abund.	Freq.	Scarce	—	—	Freq.	—
16	Abund.	Freq.	Scarce	Rare	—	—	—
10	Abund.	Freq.	Scarce	Scarce	Rare	—	—
8	Abund.	Freq.	—	Scarce	—	Rare	—
7	Abund.	Abund.	Freq.	Scarce	Scarce	Rare	—
6	Freq.	Abund.	—	Freq.	—	—	—

out in the Marathon region are deformed into overturned anticlines and synclines. Because the lower Tesnus is less resistant than the originally underlying Devonian Caballos novaculite, these lower Tesnus shales and low-rank graywackes crop out on the outside flanks of novaculite ridges, which outline the anticlines, as well as in valleys that occupy synclines. Good lower Tesnus sections are found at the following localities of the Marathon uplift: Tesnus Station, Haymond Mountains, 17 miles east of Marathon on U. S. highway 90, Dimple Hill region, and Devil's Backbone. Other good lower Tesnus sections may be seen at the entrance to the Big Bend National Park and the southwest and east side of the Solitario dome (fig. 1).

Because much of the lower Tesnus is buried under unconsolidated alluvial deposits, it is generally impossible to measure and describe complete sections. However, topographic expression, vegetation cover, dips and strikes of the more resistant adjacent units, and the scattered exposures of the Tesnus, together with the results of the laboratory studies, enable one to determine the various stratigraphic units and their thickness at the different geographic locations.

The thickness of the lower Tesnus was measured in three places: between Pena Blanca Spring and the Haymond Mountains, in the east-central part of the Marathon basin, where the thickness is about 6000 feet; between East Bourland and West Bourland mountains in the west-central part of the basin, where the thickness is about 1200 feet; and in the region about two miles southwest of the Payne Hills, at the northwest margin of the basin where the lower Tesnus thins to less than 200 feet of shale. Both the change from shale to a more massive sandy facies and the rapid increase in thickness toward the southeast seem to indicate that the site of sedimentation changed from a shelf area to a subsiding eugeosyclinal basin (fig. 3) in a southeasterly direction.

The basal part of the lower Tesnus consists of brittle, well-indurated, splintery jointed, green-gray siliceous shales, which are conspicuously laminated. Individual laminae are thin and irregular. Upward in the section these highly siliceous shales change gradually to

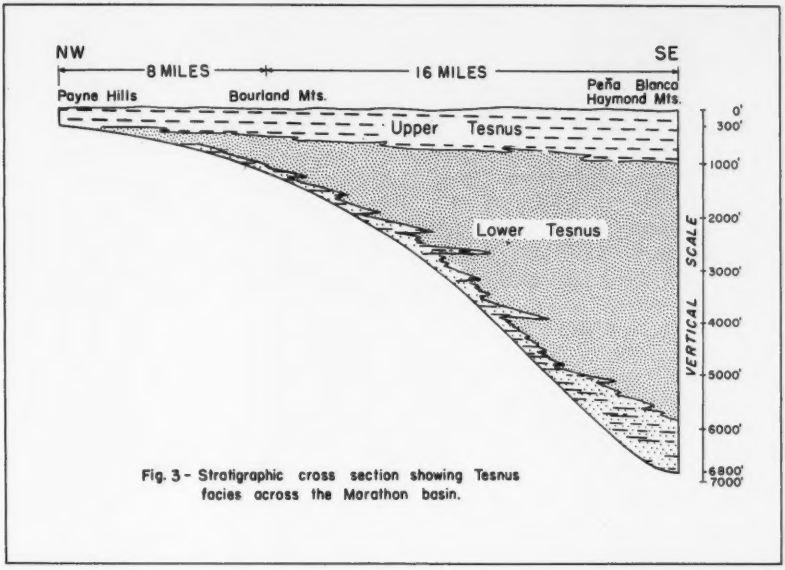

Fig. 3 - Stratigraphic cross section showing Tesnus facies across the Marathon basin.

more massive low-rank graywackes which are interbedded with numerous strongly banded siliceous shaly layers. At wide intervals, strata of hard, dense, compact, dark-green orthoquartzite are interbedded with the other rocks. Hydrous iron oxides are abundant throughout these sandy units.

The clay-mineral fractions of the shales and of the low-rank graywackes in the lower Tesnus are composed of illite and a mixed-layer chlorite-vermiculite. The amount of quartz present differs slightly from stratum to stratum. The size of the quartz grains varies also from layer to layer (tables 1–3). The numerous changes in color of the lower Tesnus are caused (1) by the changing ratio of one kind of clay mineral to another, (2) by the change from quartz to the clay minerals, and (3) by the degree of oxidation and weathering of the clay minerals.

Although the scarcity of feldspar in the lower Tesnus formation may be explained possibly by the destruction of large grains during and after their transportation, this possibility does not appear likely. The scarcity of feldspar is probably best explained by the idea that most of the source rocks were aphanitic acidic igneous rocks such as rhyolite or felsite. The abundance of magnetite in all the fourteen thin sections examined, the presence of subeuhedral augite, together with the presence of certain kinds of clay minerals, have led the authors to believe that some basalts were also exposed in the source area, that is, southeast of the present Marathon-Solitario trend, during the time the lower Tesnus beds were being deposited.

Fossils were looked for in the field, but no megascopic fauna was found in the lower Tesnus beds. However, conodonts are fairly abundant, and radiolarians are few and poorly preserved in the dark siliceous shales and can be seen under the microscope. The presence of these fossils demonstrates that this stratigraphic unit was laid down in a marine environment, or that at least

some parts of it were laid down in that environment. This fauna has not yet been studied in detail.

Upper Part of Tesnus Formation

The upper Tesnus unit consists essentially of non-resistant, fine-grained, detrital sediments. Consequently, the outcropping of the lower Tesnus is governed by the presence of the more resistant overlying Dimple limestone of Pennsylvanian age which has protected these shales from erosion. Good exposures of the upper Tesnus unit are found in the following localities, all in the Marathon basin: south of Tesnus station, flanks of the Haymond Mountains, southwest of the Dimple Hills, foot slopes of the West Bourland Mountain and the low hills immediately west of it, and south of the Payne Hills (fig. 1).

The thickness of the upper Tesnus was determined in three places: (1) a half mile southeast of Haymond Station in the east part of the basin, where the thickness is about 800 feet; (2) the north flank of the West Bourland Mountain, where the thickness is about 350 feet; and (3) in the region just south of the Payne Hills, where the upper Tesnus is about 100 feet thick. These figures indicate that the upper Tesnus unit, as well as the lower, thickens to the southeast, although this increase is much less spectacular in the upper than in the lower Tesnus unit. The upper Tesnus unit does not change facies toward the southeast (fig. 3).

In contrast to the siliceous shales and massive low-rank graywackes of the lower Tesnus, the upper Tesnus consists mainly of bentonitic, platy, nonmarine shales, ranging from gray to carbonaceous black in color, and contains interbedded black cherty layers.

Six shale samples were studied by X-ray analysis. Two were from a locality one-half mile south of Haymond Station, two were from the north side of the West Bourland Mountain, and two were samples from the south side of the Payne Hills. Illite and montmorillonite were found to be the major components of the clay fraction in all these samples. The absence of the chlorite-vermiculite clay mineral is conspicuous.

Although conodonts and radiolarians have been found in the lower Tesnus beds, they seem to be absent from the upper part of the Tesnus formation. However, fossil wood fragments are numerous.

According to Grim (1953), if an igneous rock, containing large amounts of magnesium and potassium, weathers under conditions of poor drainage, the magnesium and potassium will be retained for a long time in the products of weathering and after they are released from the source rocks, illite and montmorillonite will be the alteration products. If this is true, then the composition of the upper Tesnus beds, with their illite and montmorillonite, suggests that pyroclastics were the source material, the weathering products of which were subsequently carried to the place of deposition of the upper Tesnus beds.

The abundance of illite and montmorillonite, the absence of marine fossils except close to the overlying Dimple limestone, and the abundance of wood fragments suggest that the upper part of the Tesnus formation is predominantly nonmarine, except for the extreme upper part which contains foraminifera.

The foraminifera near the top of the upper part of the Tesnus formation have been assigned to the "lowermost Pennsylvanian" by Harlton (Powers, 1928), and the wood fragments to the Pottsville (also basal Pennsylvanian) by White. If this is true of the upper Tesnus, then the lower Tesnus may be pre-Pennsylvanian or Mississippian.

Recently a Pennsylvanian crustacean, *Tesnusocaris goldichi* Brooks, has been reported (Brooks, 1955). Judging from the lithologic texture of the shale in which this specimen was found, the authors believe it came from the basal part of the upper Tesnus.

CONCLUSIONS

Based on the present investigation the following conclusions are made:

1. All previous workers have regarded the Tesnus as one formation. However, this study offers evidence that the Tesnus formation actually contains two basically different stratigraphic units, one marine and one nonmarine. These units have different fossils, lithologies, compositions, thicknesses, and ages.

2. During the time the lower part of the Tesnus formation was being deposited, rapid subsidence, accompanied by rapid deposition, was taking place in the southeastern part of the basin while in the northwest, slow deposition was taking place in a stable shelf environment.

3. The predominantly nonmarine upper Tesnus shale is a deposit derived from the weathering of pyroclastic rocks and was laid down under fairly stable and prevailingly terrestrial conditions.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 26, NO. 3, PP. 268–275
FIGS. 1–4, SEPTEMBER, 1956

METHODS AND PRELIMINARY RESULTS IN A STUDY OF MINERALS FROM THE EASTERN GULF OF MEXICO[1]

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ABSTRACT

The special problems of mineralogical studies of ocean bottom sediments are discussed, and methods of preparation and study described which are particularly applicable to these problems. The abundance of minerals in samples from the eastern Gulf of Mexico varies greatly, and their distribution in relation to fragments of organic origin can be correlated with the bottom topography.

INTRODUCTION

The study of minerals found in ocean-bottom sediments is complicated by a number of special conditions not found in dry-land or river samples. These difficulties arise from the large areas to be covered and the practical problems of getting a sample from under water. In spite of many recent developments by which we can accurately locate the position of the ship, sampling is still somewhat a matter of chance. The coring tube drops through the water, is driven into the ocean bottom below the ship, and with luck an undisturbed core from the sea-floor is hauled up at the end of a wire which may be more than a mile long. Meanwhile the ship is drifting, and it is never possible to go back and get another sample at precisely the same spot. In an area where the slopes are steep or the lithology changes, one never has enough samples to make as detailed a study as one would like; the significance of small changes in slope or in the character of the sediments does not appear until the material has been brought back and studied in the laboratory.

SPECIFIC PROBLEMS IN MARINE MINERALOGY

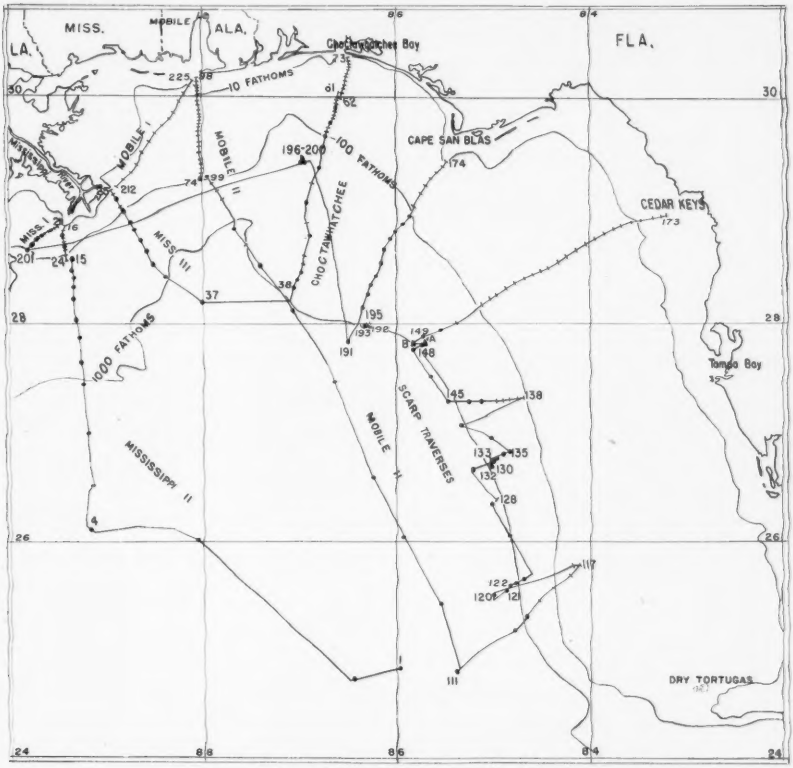
Although much work has been done in mapping and describing marine sediments, there still remain vast areas of the ocean where we have no knowledge of the character of the bottom, and even in regions where studies have been made, our information is scanty by dry-land standards. The writer is at present engaged in a study of minerals from the eastern Gulf of Mexico, covering an area about the size of New England. The *Atlantis*, research vessel of the Woods Hole Oceanographic Institution, cruised in these waters in 1951, taking observations and samples at a total of 225 stations, but at some of these, no sample could be obtained, either because the bottom was hard rock, or because of mechanical or weather troubles. The best coverage of an area would be obtained by locating the stations in a grid pattern, with the size of the grid determined by the problems to be studied, but that is not practical at sea. The track chart (fig. 1) shows the various courses sailed in order to locate the stations along lines which are continuous from close inshore out into the deep water of the central Gulf. The number of traverses which can be made is limited by the time available; along each traverse the stations are closer together inshore because of the increasing mechanical difficulties as the water deepens.

METHODS OF PREPARATION

A mineralogist approaching the study of such an area as the eastern Gulf of

[1] Contribution No. 798 from the Woods Hole Oceanographic Institution.

Mexico must bear these factors in mind in his choice of methods of preparation and analysis of the material. In most cases, oceanography being still a young field of science, he will start with a blank map; the nautical charts have such notations as "Mud," "Sandy," "Rocky," but that will be the extent of his information about the character of the sediments he is to study. In an area of any size, there will necessarily be a wide range of material to handle: coarse and fine, uniform and mixed. In order to arrive at results which will be



GULF OF MEXICO, EASTERN PART

STATIONS OCCUPIED DURING ATLANTIS CRUISE, 1951

SPONSORED BY WOODS HOLE OCEANOGRAPHIC INSTITUTION

FIG. 1.—Traverses along which samples were taken. At those stations represented by round dots, long cores (not included in the present study) were taken as well as Phleger cores or scoop samples. At stations marked by triangles, a rock dredge was used. At the remaining stations, either short cores or scoop samples were collected. The stations are numbered in the order in which they were occupied, so that they are not necessarily consecutive along any one traverse.

comparable over the whole area, each sample must be treated in a similar way. Due to the small size of the coring tube and the fineness of deep water sediments, the material available for mineralogical study is often very small in quantity. This unfortunately makes it impossible to use procedures such as feldspar staining or magnetic separation which are so useful in most mineralogical studies. Where the total weight of heavy minerals is one milligram or less, for example, it is impractical to try to separate the magnetic grains and weigh them separately, as mechanical losses will be far too large in proportion to the total sample. Fortunately optical methods can be applied to samples of any size, and have the added advantage that they do not affect the sample itself, as chemical methods do. For these reasons the writer has come to depend chiefly on the polarizing microscope, with which it is possible, in most cases, to identify even single grains.

In the literature on sedimentary petrography there are many different methods described for the preparation of samples, but they assume an ample supply of material, and advise choosing a method of treatment particularly suitable to the kind of sediment to be studied. For the reasons given above, it is considered preferable in this case to use the same basic procedure for all samples, of whatever kind or size. As interest in submarine geology increases, more and more workers will be drawn into this field, so that the following account of the preparation procedures worked out by one "submarine mineralogist" may be of interest to others who have met or will have to solve similar problems.

The samples being considered here have been collected by two different devices: the Phleger bottom sampler (described in Phleger and Parker, 1951, pp. 3–4) which provides cores one inch in diameter and up to 1½ feet long, of which the top half inch is being studied at present; and a scoop (either a commercial orange peel or the dredge described in Stetson, 1938, pp. 7–8) which brings up as much as a pint of material, but this is mixed and not a stratified core. Cores are taken wherever possible, but the tube will only penetrate soft sediments, and the scoop must be used whenever hard sand is found. In practice this is usually close to shore.

In the laboratory, the samples are first sieved, weighed, and a mechanical analysis done in the usual way; this is outside the province of the strictly mineralogical study. Similarly, the organic material, although of great importance, has here been ignored as far as possible, and the identification of shells and foraminifera has been carried out by others. The mineralogist, then, begins with a dry, clean sample of all the material larger than .074 mm; the grains smaller than that, which passed through the 200-mesh sieve, have in this study been discarded after the mechanical analysis and would in any case be too fine for satisfactory microscopic identification.[2]

The first step is to look over the samples and see if any of them have large pieces of material which would stick in the funnel and make trouble later. If they do, pass the sample through a 20-mesh sieve; if this coarse fraction is all shells, the mineralogist can ignore it, but if it appears to be rock fragments, it will have to be broken up, using such methods as described by Krumbein and Pettijohn (1938, pp. 310–314) and added to the original sample.

Next, separate the light and heavy minerals, by floating the light minerals in bromoform. As this is a standard procedure (Krumbein and Pettijohn,

[2] X-ray diffraction methods have not yet been applied to material from this area. It is hoped that a correlated study, using optical methods as described here on the fraction coarser than .074 mm in diameter, and X-rays on the finer fraction from the same cores, can be carried out in the near future.

1938, p. 343) there is no need to describe it here.

If the light fraction is made up chiefly of foraminifera, they will mask any minerals present. Some of the foraminifera, particularly those in which air is trapped, will float in a liquid of specific gravity 2.51. Although there are minerals with a lower specific gravity than this, they are not those which are likely to occur in significant amounts in ocean bottom sediments. Therefore, with samples in which foraminifera predominate it is worth while to make a second separation in the same manner as the first, using a mixture of bromoform and acetone such that the specific gravity is 2.51. This is a good use for the bromoform washings from the first separation, as bromoform can seldom be recovered pure enough to have its standard specific gravity of 2.87.

Then the separate fractions must be weighed; in the case of very small samples, the danger of loss in handling can be reduced by the following procedure: weigh the empty bottle or vial in which the sample is to be kept, add the sample from the filter paper on which it was caught after separation, and weigh the bottle plus the sample. This requires an extra weighing as compared with using a weighed beaker for measuring the samples, but is more accurate with very small samples.

METHODS OF STUDY

The final problems remaining before one actually begins to identify and count minerals, are to decide in what medium to mount the samples, and how to select that part of the sample to be examined. Krumbein & Pettijohn (1938, p. 343) recommend permanent mounts of canada balsam and piperine for the light and heavy minerals respectively. These have obvious advantages and are widely used. The writer feels, however, that where identifications must often be made on the basis of very few, or even single grains, the greater flexibility of immersion oils makes them preferable. A grain can often be turned so that it can be observed in different orientations, and if necessary it can be removed from one liquid to another until the indices of refraction are determined. Also, if it seems advisable to make X-ray studies of some baffling mineral or to dissolve the sample in acid to eliminate organic material, it is far easier to wash off the oils than to remove grains from a hard mount. As each slide is finished, it is washed with acetone onto a filter paper, and the grains put back in the bottle when they are dry.

The method used to select the grains for study is determined by the size of the sample. Where the sample is very small, one simply taps the entire contents of the bottle into a drop of oil on the slide. Where the sample is large, a microsplitter[3] can be used to bring it to a manageable size. But most of the samples from the eastern Gulf of Mexico are too big to examine all at once and yet so small that even a microsplitter is too crude. A number of methods have been tried, and the one used by the author for most samples has been quick and easy to do and at the same time seems to obtain a sample representative of the whole. If the depth of the sample in its bottle is not more than about a quarter of an inch, one can moisten a fine needle by rolling it in the drop of oil standing ready on a slide, and dip the needle straight into the bottle, being sure to go to the bottom. The needle must be withdrawn carefully, so that all the grains which have stuck to it will be transferred to the slide. This is repeated until a large enough sample is on the slide, perhaps one or two thousand grains.

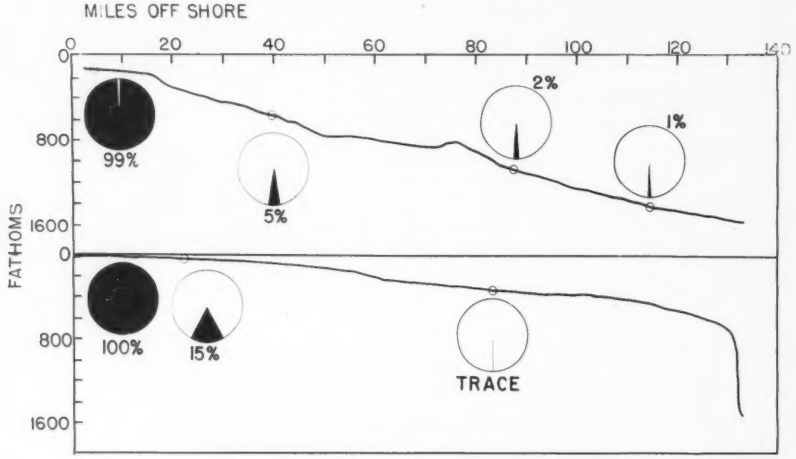
In order to test the validity of this method as compared with splitting, in one sample several slides were prepared by each method, and detailed counts

[3] Similar to a Jones sample splitter (Krumbein & Pettijohn, 1938, p. 45) but smaller, with the splitting compartments about 3 mm in width and pans $5\frac{1}{2} \times 2\frac{1}{2} \times 1$ cm.

made of every slide. The variation between slides was noticeably less in the group of slides where the needle had been used than in that prepared with the splitter. However, if the depth of the sample in the bottle was over a quarter of an inch, the variation between slides increased rapidly so that the sampling error became too great.

All the minerals in a slide are then identified, and a count made. The number of grains counted depends on the number of mineral species present, and their abundance with respect to organic material. At least 200 grains of the light and of the heavy minerals are counted (Dryden, 1931), but where the slide is mostly organic remains (shells and shell fragments, sponge spicules, worm tubes, fecal pellets, and so forth) it may be necessary to examine thousands of grains in order to find even a few minerals. The writer begins the count (after the minerals present have been identified) by counting every particle. If after several hundred have been counted it appears that the organic-mineral ratio is greater than 100 to 1, only minerals are counted, and an estimate made of the total number of grains in the slide. If necessary, more than one slide is made in order to find a reasonable number of minerals.

In some cases, the amount of organic material is so overwhelming that the minerals must be concentrated chemically. Dissolving the sample in dilute hydrochloric acid unfortunately does not solve the problem as neatly as one would hope. Many shells or tests contain



MINERAL ABUNDANCE ALONG BOTTOM PROFILES
EAST GULF OF MEXICO

Vertical Exaggeration X20

FIG. 2.—Minerals are represented by the black portions of the circles, and fragments of organic origin by the white segments. The upper profile is along the Mississippi II traverse (See fig. 1), and the lower one is Choctawhatchee; for the sake of clarity not all the stations on either line are indicated in this figure.

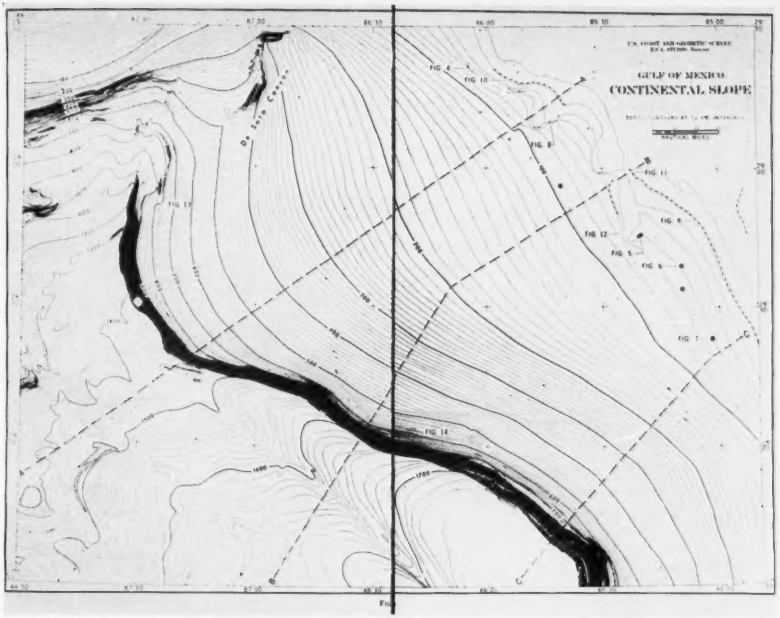


FIG. 3.—A portion of the scarp off the west Florida coast (After Jordan, 1951).

chitinous or other material which is insoluble in acid; hence the residue after acid treatment is so full of a very fine brown sludge that the minerals are still quite effectively masked. The following procedure is not ideal, but is the best that the writer has been able to find. The sample, after microscopic examination as described above, is put in dilute hydrochloric acid (1:10). After effervescence has stopped, most of the cloudy liquid is decanted, and the remainder, solid and some liquid, put in a separatory funnel. If the sample is small enough, the acid treatment can be done right in the funnel. Water is added, and the whole shaken. A few minutes are allowed for settling; as soon as all the material which looks coarser than 200-mesh has settled, the sediment is drawn off onto filter paper and the remainder discarded. The paper is washed several times with fresh water and allowed to dry. The residue is weighed and studied under the microscope as before, and the ratio of minerals to organic remains determined again. The dissolved material is assumed to be all organic, unless acid-soluble minerals were found in the first microscopic examination.

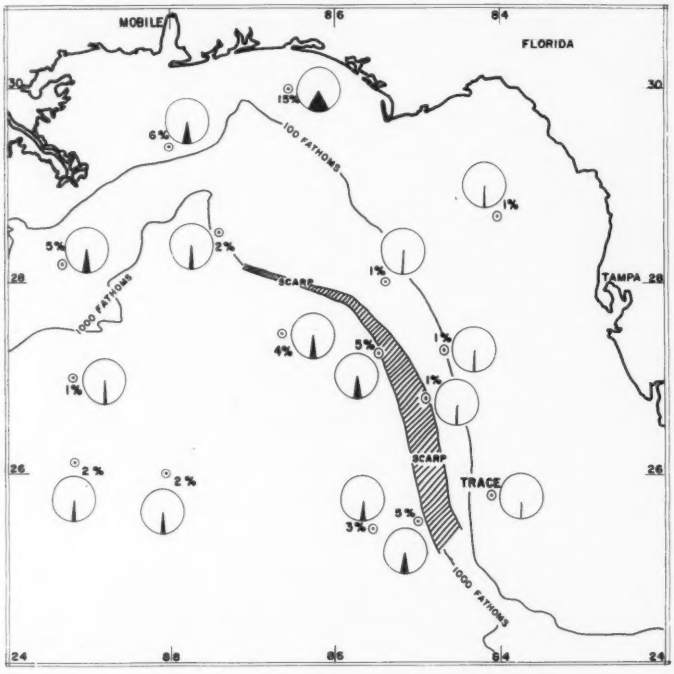
PRELIMINARY RESULTS

In drawing any conclusions from a study of this sort, one must keep in mind the fact that one is dealing with only a part of the whole sample: that fraction coarser than .074 mm diameter. The following statements apply only to this relatively coarse material, and may be severely modified by future studies of the clay fraction.

The ratio between minerals and material of organic origin has proved to be significant in the eastern Gulf, where the

proportion of minerals decreases with increasing distance from the coast. The circle diagrams and percentages in figure 2 illustrate this distribution: near the coast, minerals predominate, while about thirty miles and more off shore, shells make up more than ninety percent of the samples; in some cases the mineral-organic ratio is more than one to a thousand. Not enough samples have yet been studied to determine how distance from shore, river discharge, depth, and steepness of slope affect the change from coarse, rounded quartz sand about a half millimeter in diameter near the beach, to a fine sediment of shell fragments off shore.

Figure 2 also shows the two main kinds of bottom topography found in this area: an irregular but steady downward curve with no marked break in slope, such as is found off the Mississippi Delta, and a smooth, nearly flat plain ending abruptly in a major fault scarp, which is characteristic of most of the northern Florida Gulf coast (fig. 3 and Jordan, 1951). The *Atlantis* traversed this scarp seven times in order to cover as much of the



GULF OF MEXICO, EASTERN PART

RATIOS OF MINERAL GRAINS TO SHELL FRAGMENTS

FIG. 4.—Minerals are represented by the black portions of the circles, and fragments of organic origin by the white segments. The scarp area is represented by hatching; it extends further to the east and south beyond the area covered by this study. For the sake of clarity not all the samples studied have been represented by circle diagrams, but they all, so far, follow this pattern of distribution.

area as possible. But where on land such a cliff with rock outcropping all along it would be a mine of information, and would be intensively mapped, here it is covered by over a mile of water, and we must content ourselves for the present with 34 samples from a scarp 300 miles long and 3000 to 7000 feet high.

So far, minerals from only ten samples in this area have been studied, but they suggest an unexpected mineral-shell relationship (fig. 4). In this area, as is usual off shore, the minerals comprise five percent or less of the total. But even though there are few minerals available, their distribution varies significantly. Above the scarp to the east, minerals are almost absent: in one case there are more than a thousand grains of organic origin for each small chip of quartz, and there is no other mineral species at all. But immediately below the scarp, minerals are more abundant, ranging from three to five percent of the total sample; there is also a large variety of minerals, as many as twenty different species being found in one sample.

CONCLUSION

Where do these minerals come from? If they had been washed over the scarp from the Florida coast they should also be present above the scarp. If they are derived from the west, from the Mississippi and the other rivers of the central Gulf coast they should increase steadily in abundance up to the river's mouth. That is not the case in the samples studied so far; in the deep water samples the mineral frequency decreases toward the west, and a higher mineral concentration only reappears near the coast. The most likely source seems at present to be the rocks of the scarp itself; the few rock fragments collected are a fine limestone marl made up of foraminifera, but much of the Florida section may be present. Future work will have to confirm this relationship or lead to some other hypothesis. As more of the samples are examined, detailed comparisons will be made of the distribution of different mineral species, and a clearer picture should emerge of the mineralogy of the eastern Gulf of Mexico.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 26, NO. 3, PP. 276–283
FIGS. 1–6, SEPTEMBER, 1956

A VOLUMETER FOR MEASURING POROSITY OF INCOHERENT SANDS

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ABSTRACT

Equipment is described for measuring porosity of incoherent sand by a wholly volumetric method. The simple, lightweight apparatus is suited for use at temporary field bases. The apparatus consists of a thin-walled metal sample barrel of known volume for obtaining bulk volume of the sample, a long-stemmed glass volumeter for measuring aggregate grain displacement in water, and a manual stirring device. The method is best suited for determination of porosity in loose, moderately clean sand deposits such as beaches, dunes, and river bars. Estimated error of the measurement method is 1.3 percent. The dispersion in a set of duplicate determinations is 2 percent of the mean value because of variations in sampling procedure.

INTRODUCTION

Described as follows is an apparatus for porosity determinations that are to be performed on incoherent material such as beach, dune, or river sand. Such apparatus is sturdy, simple to operate, and independent of laboratory facilities. It takes advantage of the volumetric method by which the porosity is given as:

$$P = \left(1 - \frac{Vg}{Vt}\right) 100 \qquad (1)$$

where P is the porosity in percent, Vg is the grain volume, and Vt is the bulk volume of the sample.

DESCRIPTION OF APPARATUS

In figure 1 are shown the dimensions of the various parts of the sampling device. Total sample volume, Vt, is obtained from the known inside dimensions of the sample barrel, which is a thin-walled aluminum tube, beveled at one end on the outer circumference. The square bottom plate is used to hold the sand in the sample barrel.

In figure 2 is shown the pyrex glass volumeter in which grain displacement, Vg, is measured.

The manual stirrer, which is inserted downwards through the funnel and stem into the bulb, is wrapped with rubber tape to decrease volumeter breakage hazard.

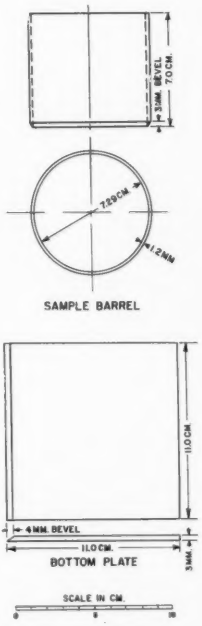

FIG. 1.—Porosity sampling equipment for use in unconsolidated sands.

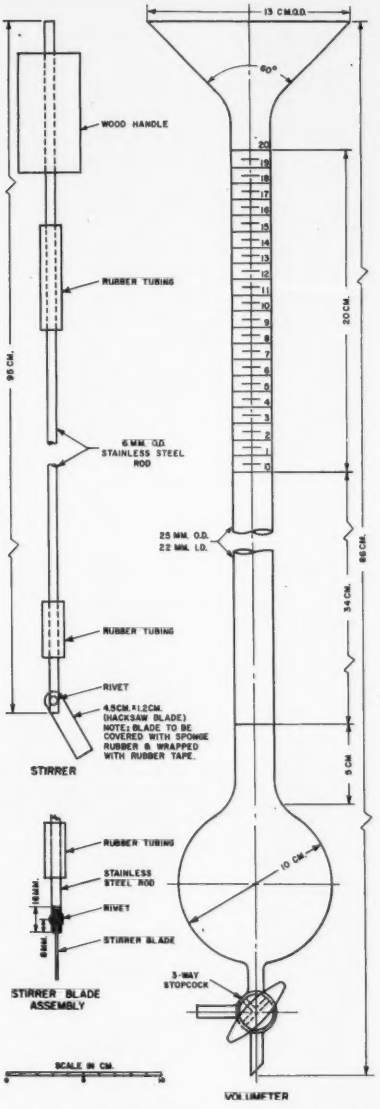

FIG. 2.—Volumeter and manual stirrer for porosity measurement of unconsolidated sands.

OPERATION OF APPARATUS

A sample barrel, bottom plate, spatula, soft brush, and sample container are taken to a sampling site. The sample barrel is pressed into the sediment body until the upper circumference is approximately 1/4 inch below the sand surface. To emplace the bottom plate, a shallow burrow is made by hand alongside the barrel so that the plate can be pushed under the barrel flush with the bottom circumference. Caution must be exercised in digging the burrow since too deep a hole may undermine the sand plug in the barrel. When the bottom of the barrel is completely covered by the plate, the assembly is lifted from the bed. The sand plug is trimmed level with the upper circumference of the sample barrel by gentle scraping with the spatula. Excess sand adhering to the outside of the barrel and plate is removed by using the soft brush.

The sand in the barrel is transferred to a suitable container that is wide enough at the mouth to slip upside down over the upper end of the sample barrel. By inverting the barrel and container simultaneously, grain loss during transfer can be reduced to a minimum. The grains adhering to the inside of the sample barrel are brushed into the container. The loose sample is then dried and gently disaggregated with a rubber pestle.

The volumeter, mounted with clamps on a ring stand is filled with water to the encircling reference mark near the base of the stem. Water is introduced into the bulb through the sidearm on the stopcock by means of a rubber hose and funnel which serves also as a leveling device for the meniscus. The stopcock is turned to a closed position and the entire loose sample is poured slowly into the funnel at the top of the stem.

Before insertion into the volumeter the stirrer is wetted and drained so that there will be no net loss of water from the volumeter when the stirrer is removed. The stirrer is then inserted into the bulb and the blade is made horizontal

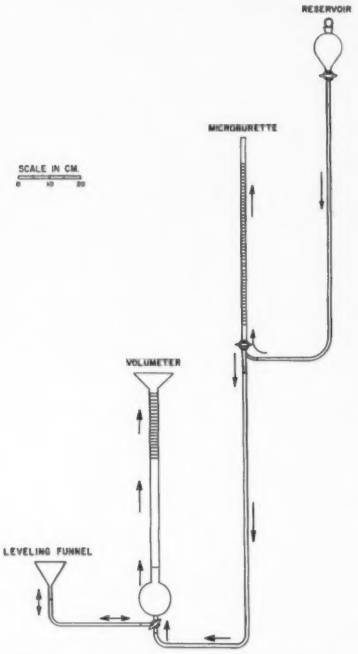

FIG. 3.—Arrangement of apparatus for calibration of the volumeter. Arrows refer to direction of flow.

by manipulation of the stirrer against the sand. The stirrer is rotated violently by hand for a period of 5 to 10 minutes or until air bubbles no longer rise from the sand. This is to promote thorough saturation of the sand. The stirrer is then removed and drained into the funnel; the reading of the water meniscus in the stem is taken and recorded. This reading is proportional to the aggregrate grain volume, *Vg*. Conversion of stem reading to porosity is made, using a diagram. The sand in the bulb can be recovered for further study by inverting the volumeter and flushing the contents into a large beaker, using a stream of water.

CALIBRATION

The volumeter is calibrated using the apparatus shown in figure 3. A microburette of 10 ml capacity, graduated in intervals of .02 ml, is suitable for metering the water into the volumeter. Care must be taken to free all lines of air bubbles. After ascertaining the volume of the stem between the lower encircling mark and the zero line, readings of volume are taken at every fifth mark on the stem. From these data a plot is constructed of volume (above the lower mark) against the stem reading (fig. 4). The volume above the lower mark is *Vg*.

Knowing the volume of the sample barrel, *Vt*, and the equation of the previously established calibration curve that gives *Vg* for all stem readings, a plot is prepared of porosity against stem reading (fig. 5). This plot obviates field calculations. The range of porosity that can be measured with the described volumeter is limited by the length of the calibrated part of the stem. The calibration line shown in figure 5 indicates that porosities ranging from 31.2 percent to 57.0 percent can be measured with this particular instrument.

ACCURACY AND PRECISION OF THE METHOD

By accuracy is meant the approach of an experimentally determined porosity value to the "true" porosity of the sample. By precision is meant the degree to which repeated measurements of the same sample tend to scatter about their mean value. Excellent replicability of a measuring method offers no assurance that a "true" estimate is being obtained.

Deviations of sample porosity from the mean porosity of a natural sand deposit arise from systematic or pattern variations in the area sampled and from random local variations in porosity that occur among points in the bed less than 1–5 cm apart. The accuracy of estimation of mean porosity depends on the number of samples taken, standard de-

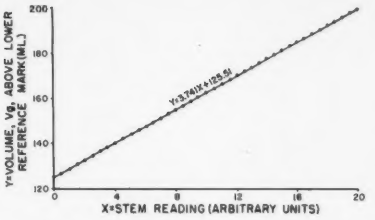

FIG. 4.—A typical volumeter calibration curve.

viation of the population sampled, and accuracy of sampling and measuring techniques.

A test of accuracy of a measurement method usually can be little more than a comparison with "accepted" or "best" methods that are themselves not error free. In determining the accuracy of the volumeter method, porosity values obtained with the instrument are compared with those obtained by a method that is dependent on the ratio or bulk density to grain density (Nutting, 1930, Griffiths, 1949, Rosenfeld and Griffiths, 1951). The technique of performing the comparison is complicated by the fact that during the volumetric analysis procedure, the form, packing, and hence original porosity of the sample are destroyed. The sample as originally constituted thus cannot be analyzed subsequently by a different "accepted" procedure. Furthermore, the effect on the "true" porosity of introducing the sampling cylinder into the bed cannot be evaluated even under controlled conditions unless a sand test bed were to be constructed with a porosity very accurately known before sampling and spatially homogeneous within the test area. Sampling procedure is an important source of error affecting accuracy or "true" porosity, but this source of variation remains unevaluated in the absence of a totally unconsolidated, granular, porosity reference standard. In spite of this limitation, however, that part of the analysis procedure not involving sampling can be appraised for accuracy relative to a second method, *i.e.*, bulk density-grain density method.

In this comparison procedure the sampling cylinder is closed at one end with a rubber sheet, coated with oil inside and out, and placed open end up on a pane of glass. Enough dry clean test sand to fill the cylinder is stirred in a beaker with a hot water-gelatin mixture. The sand-water-gelatin mixture is then spooned and packed into the cylinder, filling it completely. The sand surface is smoothed and made level with the upper circumference of the aluminum cylinder. The filled cylinder and glass plate are then placed in a refrigerator so as to coagulate the gelatin-sand mixture. After removal from the refrigerator the solid gelatin-sand cylinder is extruded from the aluminum barrel by gentle pressing after removing the rubber sheet.

The bulk volume of the solid gelatin-

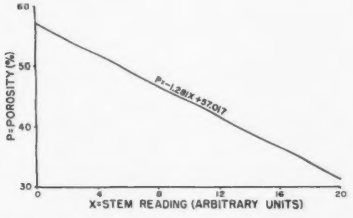

FIG. 5.—A typical computed relation between porosity (percent) and stem reading. *Vt* is 292 cm.^{3} and the equation for the calibration curve is taken from figure 4.

TABLE 1.—*Comparison of porosity measurement methods*

Percent Porosity (by bulk-grain density procedure)	Percent Porosity (by volumeter)	Difference
36.1	35.7	−0.4
36.1	36.4	+0.3
35.8	36.3	+0.5
35.7	36.3	+0.6

sand cylinder is calculated from the weight gained by a beaker filled with oil of known specific gravity when the gelatin-sand cylinder is suspended and submerged therein. After weighing in oil, the gelatin and oil are removed from the sand by repeated sequential washings with boiling water, acetone, and pentane in a filter funnel. The clean dry sand then is weighed and the bulk density calculated.

The grain density of a small sample of the sand is determined according to the common procedure involving the dry weight of the sand and the total weight when the sand is immersed in fluid in a pycnometer (Krumbein and Pettijohn, 1938, p. 501). The porosity is then calculated from the relationship—

$$P = \left(1 - \frac{\text{Bulk density}}{\text{Grain density}}\right) 100. \qquad (2)$$

Equation (2) written in densities simplifies easily to equation (1) written in volumes. No new definition of porosity is implied by equation (2), only a difference in measurement method. All of the dry clean sand sample is then introduced into the volumeter and the normal analysis procedure followed, yielding a second value for the porosity of the sand. In table 1 are shown comparative values obtained by the two methods.

The difference in the values determined by the volumeter and those determined by the bulk-density-grain-density method average ±0.45 percent or 1.3 percent (error percent).

Various factors affecting the accuracy were estimated also and their respective errors calulated (table 2). Figure 6 shows the aggregate effect of stem reading and calibration errors. The net error arising

TABLE 2.—*Instrument errors affecting volumetric porosity determinations*

Item or Quantity	Magnitude	Error
Sample Barrel		
1. Inside diameter	7.29 cm	±0.01 cm
2. Length	7.00 cm	±0.01 cm
3. Volume, *Vt*	292 cm³	±1 cm³
Microburette (used in calibrating)		
1. Upper reading	0.030 ml	±0.005 ml
2. Lower reading	9.970 ml	±0.005 ml
3. Resultant of 1. and 2. for a single run	9.94 ml	±0.01 ml
4. Cumulated volume after 20 runs	198.9 ml	±0.02 ml
Volumeter (see fig. 6)		
1. Volume above lower reference mark corresponding to any error-free stem reading (for example, 10)	162.9 ml	±0.2 ml
2. Stem reading: lower reference mark	0.0	±0.025 cm
3. Stem reading: upper reading (for example, 10)	10.0	±0.025 cm*
4. Resultant error of 2. and 3.	10.0	±0.05 cm
Vg (affected by 1. and 4.)	172.9 ml	±0.04 ml
Porosity	44.2% (example: 44.2% ±0.4% is 44.6% to 43.8%)	±0.4%†

* The range thus encompassed is 0.05 cm which corresponds to one-half of smallest stem division which is 0.1 cm (1 mm).

† When dealing with porosity data that are expressed in percentage, *error* and *error percent* must be carefully distinguished. The following illustration indicates the usage of this paper: Error of ±0.7 percent in a magnitude of 40.0 percent indicates a range from 40.7 percent to 39.3 percent; the indicated error is added or subtracted directly. Error percent of ±0.7 percent in a magnitude of 40.0 percent indicates range from 40.3 percent to 39.7 percent; the magnitude is multiplied by the error percent and the result added to or subtracted from the magnitude.

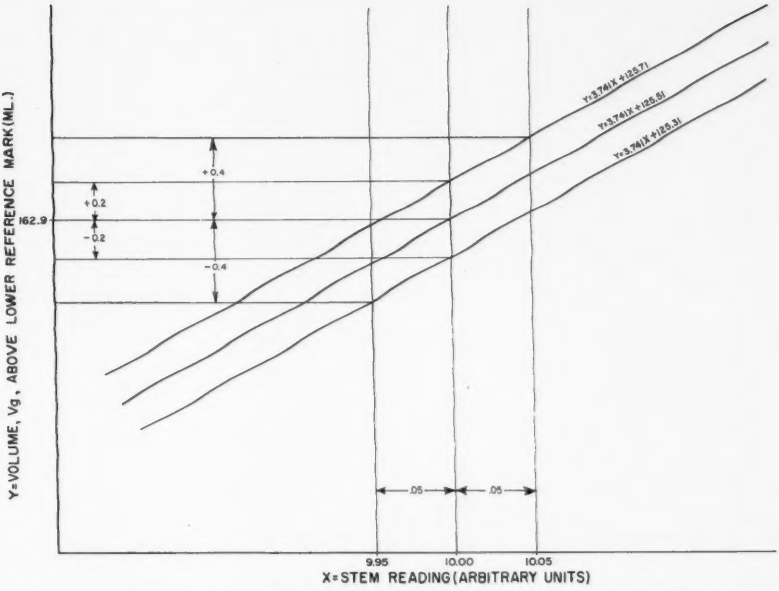

FIG. 6.—Geometric representation of the aggregate effect of stem reading error and volumeter calibration error.

from these factors is not likely to exceed ± 0.9 percent (error percent).

The precision of the method is tested by comparing the results of repetitive analyses. Each step of the sampling and analysis procedures influences the final result; however, the principal source of variation is the lack of reproducibility with which the sample barrel can be pushed into the sand bed. This source of variation can be estimated by comparing results among a set of samples taken from a small area. If this area is part of a dune or beach, for example, some part or all of the observed variation in porosity may be due to a gradient or pattern in porosity across the test area. The analysis-of-variance provides a means of separating the variation due to pattern effects from the total variation of a set taken in a natural environment. Descriptions of the technique and discussions of the assumptions are presented elsewhere (Dixon and Massey, 1951, Krumbein and Miller, 1953, Krumbein, 1953).

Several sets of samples were taken from natural environments and several sets from an artificially constructed sand test bed. The test bed was formed of sand from Colorado River, Texas. The median grain diameter is 0.70 mm and the sorting coefficient is 1.40. After drying, the sand was shoveled into a box 39 inches wide, 48 inches long, to a depth of 8 inches. This bed was mixed, raked, and then flooded from the surface with water that percolated downwards, seeping out the bottom of the box. The moisture content of the resulting sand bed is about the same as that found on many beach foreshores. Each set of porosity samples is comprised of 12 samples that were taken from the sand

TABLE 3.—*Tests of precision of porosity sampling and measurement procedures*

Line	Set No.	I	II	III	IV	V	VI	VII	VIII*
1	Location	Cape San Blas, Florida	Alligator Point, Florida	Galveston, Texas	Port Aransas, Texas	San Luis Pass, Texas	Artificial Sand Bed	Artificial Sand Bed	Artificial Sand Bed
2	Sampling area (sq. ft.)	5 beach	3 beach	19 dune	9 beach	5 beach	5 box	5 box	5 box
3	Number of samples	12	12	16	16	16	12	12	12
4	Arith. mean porosity (percent)	45.1	43.1	47.9	41.5	43.5	40.5	40.5	39.9
5	Extreme range (percent)	0.8	1.3	9.0	2.4	3.6	1.0	1.0	1.0
6	Total spread (percent)	±0.4	±0.7	±4.5	±1.2	±1.8	±0.5	±0.5	±0.9
7	Std. dev., σ_{total}, for set (percent)	—	—	±2.8	±0.5	±1.1	—	—	—
8	Std. dev., $\sigma_{residual}$, for set after pattern removal (percent)	—	—	±1.0	±0.4	±0.6	—	—	—
9	2σ residual (percent)	—	—	±2.0	±0.8	±1.2	—	—	—

* Four operators participated in this test.

bed in a regular pattern from an area of five square feet on a basic mesh of one foot.

In table 3 are shown the results of the various tests. The samples of sets I and II were taken at randomly located points within small sampling areas, and thus no analysis to separate the natural pattern variation from the experimental variation could be attempted. Results of the application of the analysis-of-variance technique to sample sets III, IV, and V are recorded in line 8 of the table. In line 9 are recorded two standard deviations which in a normal population encompass 95 percent of the total population about the mean. The figures in line 9 are thus good approximations of the total spread in data due to experimental error. Sets VI, VII, and VIII were taken from a test box in which pattern variation is negligible.

The average of the figures for experimental error of the sets excluding Set VIII is ± 0.9 percent. This is an estimate of the precision of the porosity sampling and measurement procedure. In terms of error percent it is 2.1 percent.

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FIGS. 1–2, SEPTEMBER, 1956

DISCUSSION

THE MOVEMENT OF ROCKS BY WIND[1]

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A series of recent articles on the origin of playa stone tracks in California and Nevada (McAllister and Agnew, 1948; Clements, 1952; Kirk, 1952; Shelton, 1953; and Stanley, 1955) have focused attention on the general problem of the movement of rocks by the wind and thereby suggest the possibility of this origin for exotic blocks or any coarse material in a fine-grained sedimentary deposit.

The wind-blown hypothesis of the origin of stone tracks has been rejected by Stanley (1955), who proposes an origin by icefloe rafting. Nevertheless, the formation of these tracks by rocks at temperatures that may have been above freezing is documented by Clements for an area in Nevada, and Shelton (1953) has shown that a rock weighing 19 ounces can be moved over an artificially muddied playa surface by winds not exceeding 42.2 mph created by propeller wash. However, the suggestion that rocks ranging in weight from 1 to 600 pounds can be moved solely by the wind, even on the muddy playa surface, is difficult to accept.

The writer's purpose in this discussion is simply to present briefly the results of observations made by Guilcher and Cailleux (1950) in the Netherlands and experiments performed in England by Grove and Sparks (1952) which are pertinent specifically to the origin of playa stone tracks and in general to the emplacement by the wind of pebbles and cobbles in anomalous positions in fine-grained sediments.

[1] Publication authorized by Director, U. S. Geological Survey.

Guilcher and Cailleux describe the presence of discontinuous pebble layers 10 to 20 cm below the surface of Pleistocene sands in the Veluwe Hills area of the Netherlands. These pebbles, ranging in their maximum dimension from 1 to 4 cm, are found throughout the region in positions that preclude their emplacement by stream action or solifluction. In addition, the presence of these pebbles on the surface of the sand hills, which range from 1 to 3 meters in height, in positions away from all descending gravel deposits leads the authors to an unusual explanation of their origin. The sands are thought to have been deposited by blizzards during the Würm glacial epoch, but if aeolian transport for the pebbles is assumed, then Guilcher and Cailleux postulate the unusual circumstances in which the fine-grained materials, loess and sand, were stationary while the pebbles were moved. They conclude that these conditions would be realized only on a glazed surface. The surfaces of the sand hills were covered with a coating of ice, and the pebbles from adjacent stream channels were blown up the icy surfaces by strong wind action. Guilcher and Cailleux cite as evidence an observation of pebbles being blown down an icy road by the wind, and the presence of similar pebble zones in Denmark and Greenland are mentioned with the suggestion that conditions favorable to such pebble movement might have been common in a periglacial climate.

Grove and Sparks (1952) were interested in this hypothesis as a possible explanation for similar appearing pebble patches found in the deposits of southern

TABLE 1.—*Size and weight of pebbles*

Pebble	Dimensions (cm)	Weight (grams)
a	4.9×3.9×2.7	56
b	3.8×2.9×2.0	33
c	3.0×2.5×1.9	24
d	2.6×2.0×1.6	12
e	1.8×1.8×0.9	4

England. They began wind tunnel experiments to determine the plausibility of this type of wind action, and the size of pebbles that could be moved upslope by the wind.

Grove and Sparks used beach pebbles, rounded and smoothed by marine processes, ranging in weight from 4 to 56 grams. The weights and dimensions of each pebble are given in table 1.

A thin slab of ice was placed in the wind tunnel, which is capable of producing winds up to 75 km/hr. The slope of the ice surface could be changed, and for each angle of inclination the wind velocity required to begin the upslope movement of each pebble was recorded and is presented in table 2.

The surface of the ice slabs melted slightly during the experiments, apparently further decreasing friction between slab and pebble. The data presented in table 2 reveals that even the heaviest pebble (56 grams) was moved up a 5° slope by winds with a velocity of 75 km/kr (about 47 mph). Further experimentation showed that once movement was begun it could be maintained on a slope up to 5° steeper by winds of the same velocity. During the experiments the two lightest pebbles (d and e) rolled whereas the heavier pebbles slid on the ice slab. Grove and Sparks conclude that Guilcher and Cailleux were conservative in their opinions concerning the maximum size of pebbles that could be moved by the wind on a glazed surface.

TABLE 2.—*Wind velocity required to initiate movement on various grades*

Pebble	Wind velocity in km/hr			
	50	60	70	75
a	—	—	1°	5°
b	—	0.5°	5°	7.5°
c	—	1°	6°	9°
d	—	3°	16°	19°
e	—	5°	20°	20°

From graphs presented by Grove and Sparks it was possible to estimate the wind speed necessary to initiate movement of each pebble on a surface of zero slope. In figure 1 are two regression lines

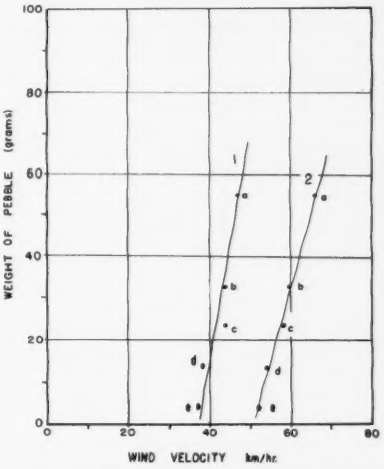

FIG. 1.—Relation between pebble weight and the wind velocity needed to initiate movement on an icy surface (plot 2) and that needed to maintain movement on an icy surface (plot 1). Letters indicate pebbles described in table 1.

fitted by estimation, the first showing the relation between pebble weight and wind velocity required to maintain movement on the horizontal ice slab, and the second showing the relation between pebble weight and the wind velocity necessary to initiate movement on the horizontal ice slab. Both sets of data reveal that the weight of the pebble moved is directly proportional to wind velocity. If this relation is extended to include cobbles and boulders

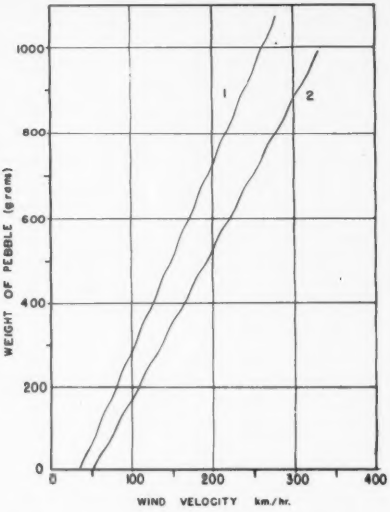

FIG. 2.—An extension of the regression lines of figure 1 to high wind velocities. Regression 1, wind velocity needed to maintain pebble movement. Regression 2, wind velocity needed to initiate pebble movement.

weighing more than 56 grams as is done in figure 2, then the wind velocity required to initiate movement of a rock weighing 500 grams is 195 km/hr or about 122 mph. The 19-ounce rock used by Shelton under these conditions would require a wind of about 133 mph to begin and maintain movement. Perhaps the downward blast of propeller wash is a more effective propelling force than winds moving essentially parallel to the surface.

The extension of the experimental data of Grove and Sparks to large size rocks, if valid, strongly suggests that only rocks weighing less than 1 pound could be moved by winds and probably only those weighing less than ½ pound or 250 grams would be moved with any frequency even on a surface of low friction such as a glazed surface.

With an initial impetus, the movement of a 1 pound rock could be maintained by winds of about 145 km/hr (90 mph), but even winds of this velocity are not common. Therefore, wind action may move the pebbles which were of such interest to Guilcher, Cailleux, Grove and Sparks but probably not many of the objects that have formed the playa stone tracks. The winds of 40 mph encountered by Kirk (1952) and Clements (1952) will move particles only up to about 50 grams or will maintain the movement of rocks up to about 130 grams in weight. It would seem then that other agents are necessary. The wind undoubtedly is the propelling force but some other factor must be introduced to move the heavy rocks. Perhaps as suggested by Stanley (1955) the rocks were dragged by ice, or in the case described by Clements where ice may not have been present, the buoying action and movements of the half inch of water on the flat playa surface under the influence of strong winds could cause rock movement.

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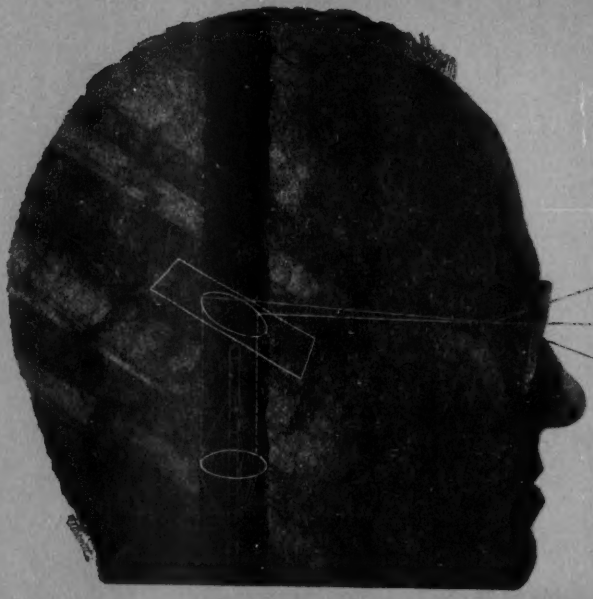

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